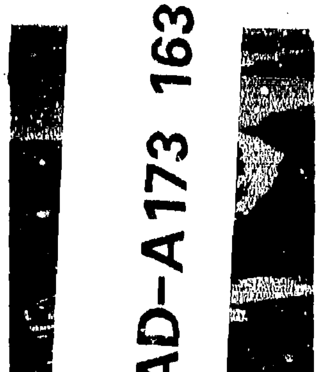
US Army Corps of Engineers



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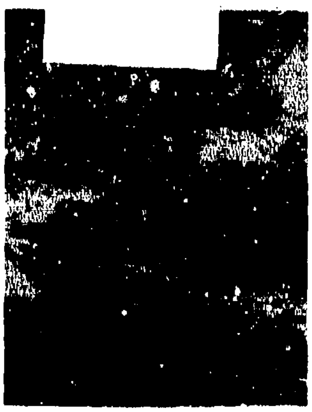

GEOTECHNICAL LABORATORY

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REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-GT-3

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

by

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Geotechnical Laboratory

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Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

August 1986
Report 1 of a Series

Approved For Public Release; Distribution Unlimited

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The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

For example, Technical Report REMR-GT-3 is the fourth report published under the Geotechnical problem area.

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The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

COVER PHOTOS:

TOP — Black Butte Dam, Tehama County, California, emergency spillway overflow, March 1983.

MIDDLE — Dmad Dam, Utah. Emergency spillway overflow in July 1983 resulted in excessive channel erosion, failure of the spillway structure, and catastrophic release of the reservoir waters.

BOTTOM — Grapevine Dam, Texas. Emergency spillway overflow of October-November 1981 caused severe erosion of the discharge channel.

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The problem of rock erosion in unlined emergency spillway channels is described in this first-of-a series report. Recent CE and non-CE case histories which illustrate the potentially hazardous impacts of excessive erosion in discharge channels are described as are the various factors controlling erosion and other responses to emergency spillway overflow. Research programs designed to improve geotechnical capabilities with respect to selection of cost-effective preventive and remedial measures in discharge channels where the risk of excessive erosion appears high are also discussed.

Response to emergency spillway overflow is controlled by a variety of hydraulic and geologic factors including flood frequency and magnitude, engineering design, discharge channel gradient(s), discontinuity of earth materials, and erodibility of earth materials. A major controlling factor of erosion in spillway discharge channels lined by sedimentary

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19. ABSTRACT (Continued).

strata appears to be the interrelated effect of stratigraphic discontinuity and channel gradient change(s). These factors combine to initiate and control headward migration of knickpoints, where resistant sedimentary layers are undercut by scouring of softer, underlying strata. In terms of erodability of earth materials, the scale of the hydraulic forces generated during emergency spillway overflows suggests that rippability and lithostratigraphic discontinuity may serve as a good point of departure in describing the relative resistance to erosion of rocks lining discharge channels.

Responses to emergency spillway flow include channel floor and bank erosion, sediment transport and deposition, and overbank flooding. Erosion of the material underlying unlined channels is the most serious of spillway flow impacts, since channel floor degradation can undermine spillway structures and threaten reservoir integrity. Responses to emergency spillway overflow are not limited to the immediate area of the dam however. Spillway overflow can act to cause stream thresholds (which limit change on the system) to be exceeded in the main channel into which spillway overflow exits and can influence or induce changes for significant distances downstream. Several case histories provide ample evidence that knickpoint migration and headcutting can be initiated at a point considerably downstream from a control structure. Sediment deposition can build bars and deltas in spillway discharge channels, at the exit channel - main channel confluence, and in downstream reaches of the main channel. Deposition in the main channel may impede passage of reservoir overflow and, by deflecting flow into the channel banks, cause irregular channel widening. This impact could conceivably initiate or accelerate erosion of streambanks and levees, impact navigation, endanger ecological balances, and increase the danger of overbank flooding.

Research is in progress to determine the quantitative effects of stratigraphic variation on erosion rates in sedimentary rocks using simulated earth materials and designed stratigraphic variability in a self-contained, recirculating and tilting hydraulic flume. Adjunct research is in progress to generate predictive erosion indices on a comparative site-specific level and to more adequately address the downstream impacts of spillway overflow. Results of this research as well as recommendations in the realm of preventive and remedial measures will be promulgated by future reports in this series.

PREFACE

This study addresses rock erosion in emergency spillway channels, a problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted by the US Army Engineer Waterways Experiment Station (WES).

This preliminary report summarizes work performed during Fiscal Year 1985, principally during the period from February to September 1985. Results of work currently in progress and ongoing research programs will be the topic of further reports to be completed during FY86 and FY87. The study was under the direct supervision of Messrs. J. S. Huie, the Problem Area Leader, and J. H. May, the Principal Investigator, Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL). General supervision was provided by Mr. J. H. Shamburger, Chief, Engineering Geology Applications Group (EGAG), EGRMD; Dr. D. C. Banks, Chief, EGRMD; and Dr. W. F. Marcuson III, Chief, GL.

Individuals contributing directly to the study and its compilation were Dr. C. P. Cameron, Associate Professor of Geology, University of Southern Mississippi; Mr. K. D. Cato, Hydrogeology Laboratory, Center for Engineering Geosciences, Texas A&M University; and Mr. C. C. McAneny, Dr. P. G. Malone, Mr. J. H. May, and Mr. J. B. Palmerton, all of EGRMD.

Corps of Engineers Districts and Divisions were major contributors to this report. The many individual contributions from District, Division, and site offices, particularly the helpful suggestions and constructive criticisms of field reviewers, are gratefully acknowledged and appreciated by WES.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per mile	0.1893935	meters per kilometre
miles (US statute)	1.609347	kilometres
square miles	2.589998	square kilometres
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	metres

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

PART I: INTRODUCTION

Background

1. Rock erosion in emergency spillway channels is one of the specific research work units being addressed by the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. REMR is a comprehensive investigation of the problems associated with the maintenance and preservation of Civil Works structures constructed and operated by the US Army Corps of Engineers (CE). The objective of this work unit is to evaluate the geotechnical and hydraulic factors influencing the rate and the mechanisms of erosion in unlined spillway channels to develop cost-effective remedial and preventive measures.

2. Only very infrequent flow in many CE unlined emergency spillways has kept the spillway erosion problems from reaching serious proportions in some Districts, particularly in the South and the Southwest. The benefit of conservative hydrologic and hydraulic design is obvious from the record--no CE spillway or dam has failed.

3. Despite this enviable record, several factors raise doubts regarding the safety of some facilities today. The most obvious is the use of revised hydrological criteria to increase the probable Project Maximum Flood (PMF) and/or the maximum Spillway Design Flood (SDF).* Demographic shifts and socioeconomic changes (particularly urban development) provide powerful impetus for increased awareness of the downstream impacts of sudden reservoir release. Urban development and associated clear-cutting impact regional

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* The SDF and PMF are not necessarily synonymous since they are based on different criteria. The PMF or Probable Maximum Precipitation (PMP) is derived from specific criteria established by the National Weather Service and in recent years has been used to develop the SDF for most CE structures. However, earlier designs derived SDF based on the transposing and incrementing of previously experienced major storms as well as criteria related to project size, type, and risk of catastrophic conditions due to failure (Engineer Circular (EC) 1110-2-27).

hydrology by increasing runoff rates and possibly the PMF. New interpretations of regional and local site geology, as well as changes in ground-water and surface-water regimes caused by increased land use on surrounding terrain, justify serious reevaluation of facility safety. Engineering surveys using new technology may determine that the materials used in construction were inadequate. The useful life of some materials may have been overestimated. Recent case histories show the fragile nature of some unlined spillway channels experiencing even a small fraction of the maximum spillway design discharge.

4. This report summarizes the current knowledge of erosion in unlined emergency spillway channels. This problem has not received much emphasis in the past except at local levels, although the importance of rock integrity and the potential impacts of erosion on spillway design criteria is clearly documented in Engineer Manual (EM) 1110-2-1603 (31 March 1964, pp 46 and 47). It has been recognized that severe scour and erosion of the rock flooring of unlined emergency spillway channels might cause spillway failure and consequent catastrophic release of reservoir waters. Such an event could endanger lives or cause substantial property damage. Engineer Regulation (ER) 1110-2-100 requires these spillway structures and their channels to be periodically evaluated for structural safety, stability, and operational adequacy. Aspects of this problem were discussed in EM 1110-1-1603 (31 March 1965). This engineering manual documents cases of severe erosion of sedimentary rock below spillways and highlights the causative effects of stratigraphic and structural discontinuities (i.e., bedding planes and vertical joints). The manual concludes that further inquiry into the record of erosion of rock downstream from spillways is needed. Other Federal agencies responsible for the construction and administration of dam facilities have also identified as an area for needed research the problem of rock erosion in emergency spillway channels. A recent US Department of Agriculture (USDA) Soil Conservation Service report, summarizing the national effort in erosion research, highlights the problem of rock erosion in emergency spillway channels and specifically recommends applied research pinpointing the effects of stratigraphic variability on the initiation and the rate of erosion.

5. Many spillways flow only occasionally and others have never experienced a flow. The ephemeral nature of emergency spillway flow makes it difficult to determine the extent, rate, and mechanisms of erosion and its impact

on downstream channels. It is difficult to design experiments or to develop empirical data bases using infrequent-to-nonexistent flow events. Hydraulic and geotechnical modelling of these processes is also difficult. Project exploration data acquired during preconstruction and construction phases are often inadequate for detailed geological or geotechnical evaluation of the erodibility of some spillway channels. The available data base is limited by a lack of significant published work on complex geologic systems in channels.

6. On the other hand, several emergency spillways which flowed during the period 1970 to 1984 amply demonstrate the need for this research. Channels were badly damaged in some cases; in others, severe headcutting and channel excavation threatened spillway structures. In a 1983 case involving a non-CE dam, spillway failure by channel erosion was responsible for the catastrophic drainage of a 15,000 acre-ft* reservoir (the DMAD Reservoir, Millard County, Utah). Over the past 15 years, financial dimensions of the damage triggered by spillway erosion processes are in excess of $10 million for CE projects. If these costs are added to those borne by other Federal agencies, states, and private interests, the total would be in excess of $100 million.

Scope

7. The major emphasis of this work unit is directed to flow and erosion effects in unlined emergency spillway channels (those floored by rock and sometimes accompanied by soils). The terms "rock" and "soil" as used in this report are defined in the Glossary of Geology (American Geological Institute (AGI) 1972) as:

a. Rock. Any naturally formed, consolidated or unconsolidated material (but not soil) composed of two or more minerals, or occasionally of one mineral, and having some degree of chemical and mineralogic constancy.

b. Soil. All unconsolidated earthy material over bedrock. Commonly the natural medium for the growth of land plants.

8. Rock types in CE unlined emergency spillway channels are as widely variable as the geologic, physiographic, and geomorphic settings of CE reservoir facilities across the nation. The physical properties of density,

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

compressive strength, abrasion resistance/hardness, porosity, and permeability also show considerable variation as do stratigraphic and structural features such as discontinuities. Locally, such variations play an important role in erosive processes during spillway overflow where the damsite is situated in a geologically complex region characterized by abrupt changes in the composition and texture of the rocks and/or derived soils. Variations in the effects of chemical and mechanical weathering can also play a role in the erosion processes affecting spillway channels.

9. This interim report analyzes the causes-and-effects of erosion in emergency spillway channels having a variety of bedrock situations. These analyses reflect geotechnical, hydraulic, hydrological, and engineering design considerations. The major findings yield an enhanced data base and improved understanding of erosion processes in unlined emergency spillway discharge channels. This information increases the capability to (a) predict spillway channel response to spillway flow, (b) develop better prediction and documentation of downstream impacts, and (c) provide a basis for planning remedial measures where warranted. The report will serve as a mechanism for communicating ideas and concepts in this problem area to interested CE personnel and their counterparts in other Federal, state, and local agencies.

10. District experience, case histories, and site visits were used extensively in the compilation of this report. These elements form the major part of the work unit data base and serve as the foundation for the development of research tasks.

Objectives

11. The overall objective of this investigation is to develop procedures for the detection, prediction, prevention, and repair of rock erosion in emergency spillway channels. These procedures will be documented in a technical report and the technology transferred in a timely manner to interested technical personnel in the CE District Offices and appropriate personnel in other Federal and state agencies working on the same problem.

12. The initial phase of this research identified the following specific FY85 objectives:

a. To establish an empirical data base documenting, if possible, all erosive emergency spillway overflow events at CE projects by accumulating detailed information from historical accounts and/or site visits.

b. To assess the magnitude, severity, and potential impact of erosion-related problems in emergency spillway channels.

c. To determine the adequacy of the currently available data base and of the methods used to predict erosion in spillway channels.

d. To assess and document remedial measures implemented to solve or impede erosion in emergency spillway channels.

e. To identify research needs for specific problem areas in erosion prediction.

13. FY85 objectives were successfully met. However, time and manpower constraints did not allow adequate attention to be given to remedial and preventive measures; therefore, further inquiry in this vital area is needed.

Case Histories

14. During the initial phase of this study, attention was largely directed to emergency spillway sites where serious erosion had either endangered facility safety, had threatened to do so, or had resulted in costly remedial or preventive measures. Onsite surveys were conducted at 25 unlined emergency spillways in FY85. Reports and data from other sites were also studied and further site visits are planned for FY86. This investigation revealed that most (but certainly not all) serious problems of rock erosion in unlined emergency spillway channels occur in gently dipping sedimentary rocks of variable cohesiveness and continuity.

15. Several recent case histories have been selected to illustrate some of the major problems of rock erosion in emergency spillway channels. Because of their common geologic settings, the following case histories comprise a prototype model for rock erosion of gently dipping stratified sediments or sedimentary rocks. The CE Divisions and Districts are shown in Figure 1. The locations of the dam projects listed below are discussed in the report text and appendices and are shown in Figure 2.

a. Saylorville spillway, US Army Engineer District, Rock Island (NCR) (Figure 2, #34).

b. Lake Brownwood spillway, Texas, (non-CE) (Figure 2, #18).

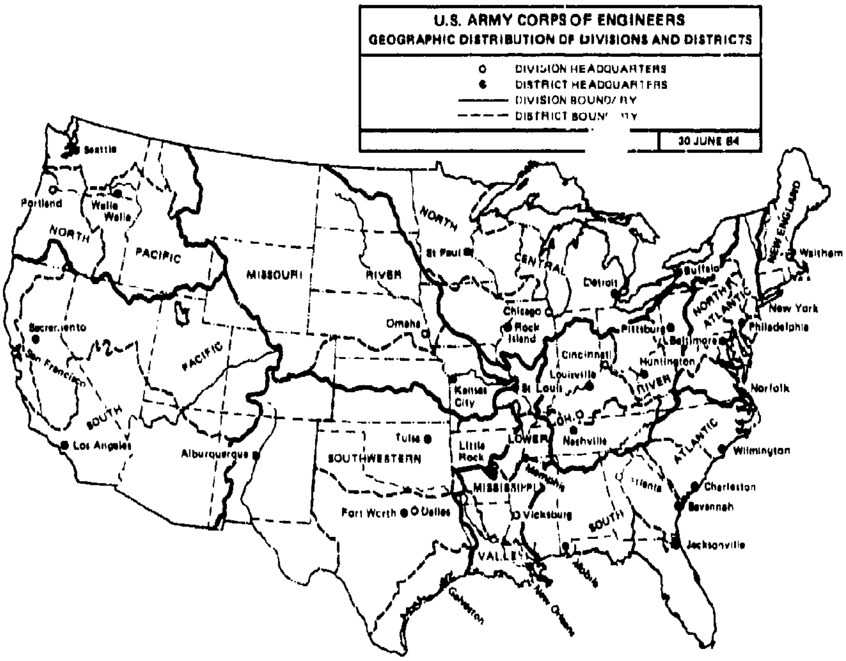

Figure 1. Divisions and Districts of the US Army Corps of Engineers

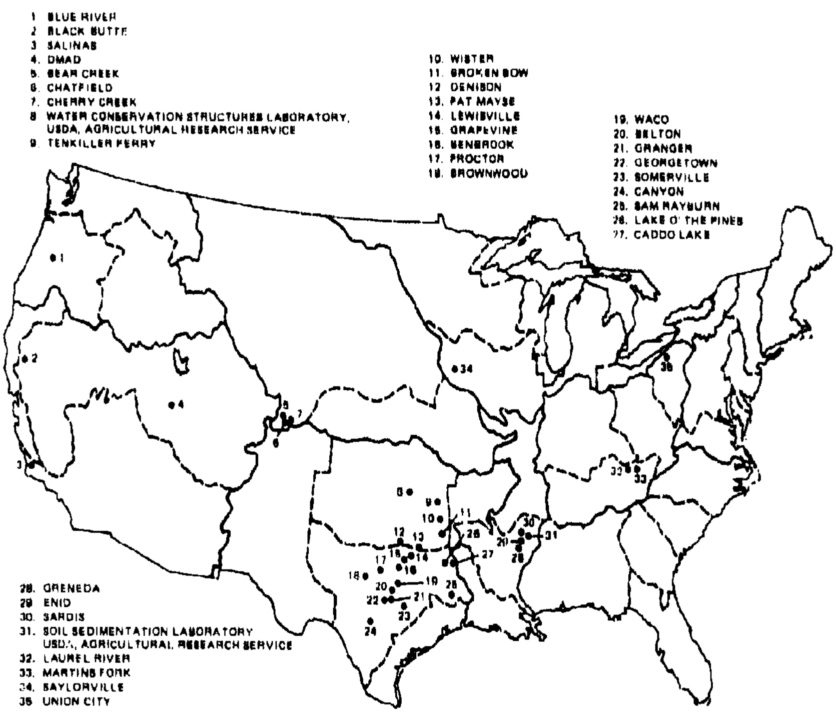

Figure 2. Locations of projects discussed in this report

c. Grapevine spillway, US Army Engineer District, Fort Worth (SWF) (Figure 2, #15).

d. Lewisville spillway, SWF (Figure 2, #14).

e. Sam Rayburn spillway, SWF (Figure 2, #25).

f. DMAD spillway, Utah, (non-CE) (Figure 2, #4).

Saylorville spillway

16. Background information. Saylorville Lake Dam (on the Des Moines River near Des Moines, Iowa) experienced emergency spillway overflow for the first time during the period 18 June to 3 July 1984 at rates approximately 9 percent of design discharge. Although the spillway structure was not endangered by this event, erosion of the rocks underlying the unlined portion was severe. Excellent studies of the spillway geology were conducted in 1981-82 in response to North Central Division (NCD) recommendations in 1979. The Division expressed concerns about the ability of the spillway to pass design floods without overtopping the walls of the spillway chute.* The 1984 emergency spillway flow demonstrated that in fact the spillway performs as per engineering design. However the excellent geological studies conducted prior to the first flow event combine with with excellent visual and detailed studies of the flood and erosion in the spillway channel to yield an outstanding observational data base for a well-documented case history of sedimentary rock erosion in an unlined emergency spillway channel. The results of these studies are contained in US Army Engineer District, Rock Island (1984).

17. As has already been mentioned, the Saylorville Lake Dam is located on the Des Moines River in Polk County, Iowa. Figure 3 shows the project location as well as the general plan of the dam, outlet works, and emergency spillway. The project, authorized by the Flood Control Act of 1958, provided for construction of an earth dam 6,750 ft long at the crest with a maximum height of 105 ft. Project construction took place in three stages (designated as Stage I, II, and III) during the period 1965 to 1975. With the pool at spillway-crest el 884.0,** the reservoir area is about 16,700 acres containing approximately 676,000 acre-ft of water. Of this, 602,000 acre-ft is allotted to flood control with the remainder being used as a conservation pool.

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* Personal Communication, NCDED-T letter to NCR, Saylorville Dam, service spillway, 16 Aug. 1979.

** In this report, elevations are in ft NGVD.

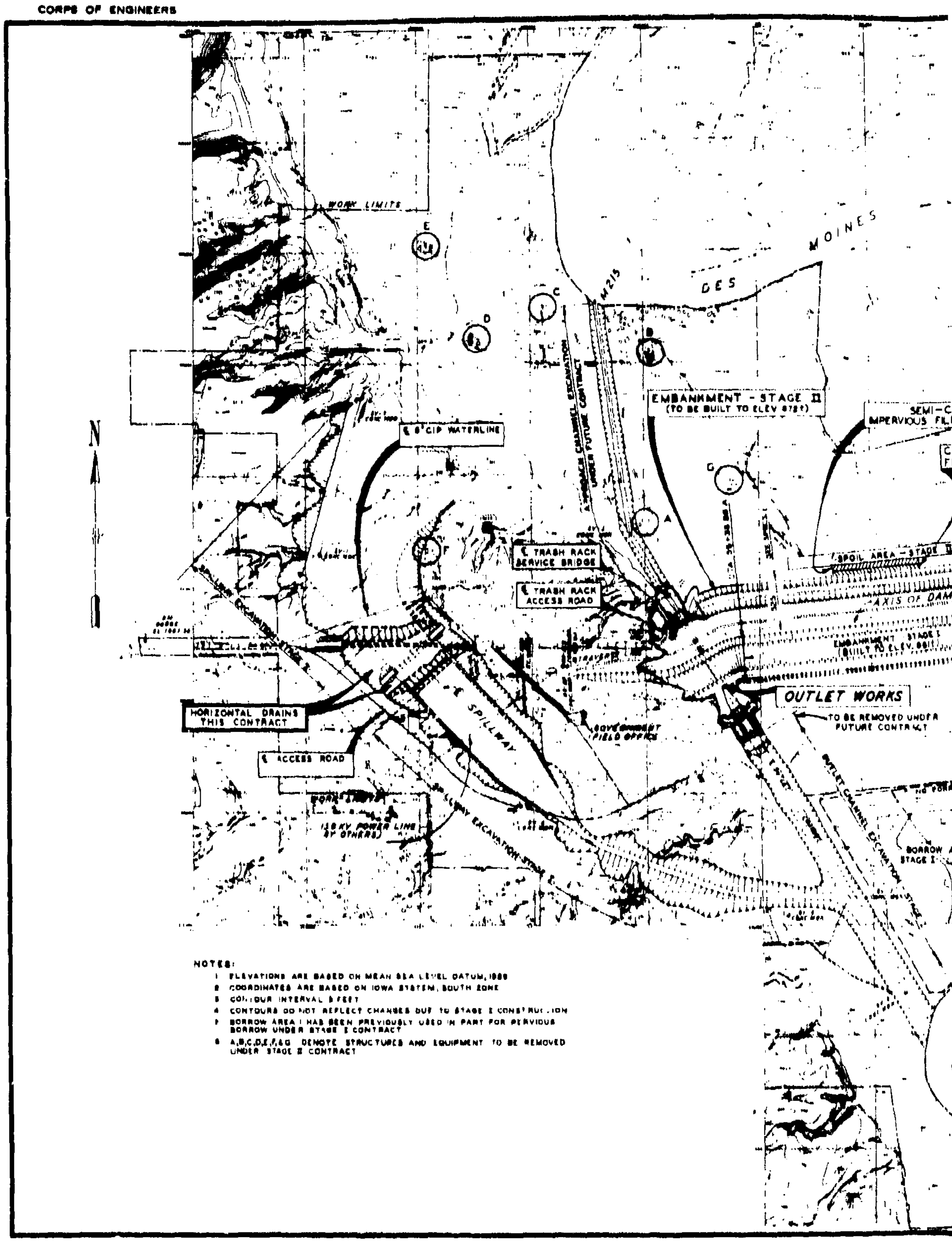
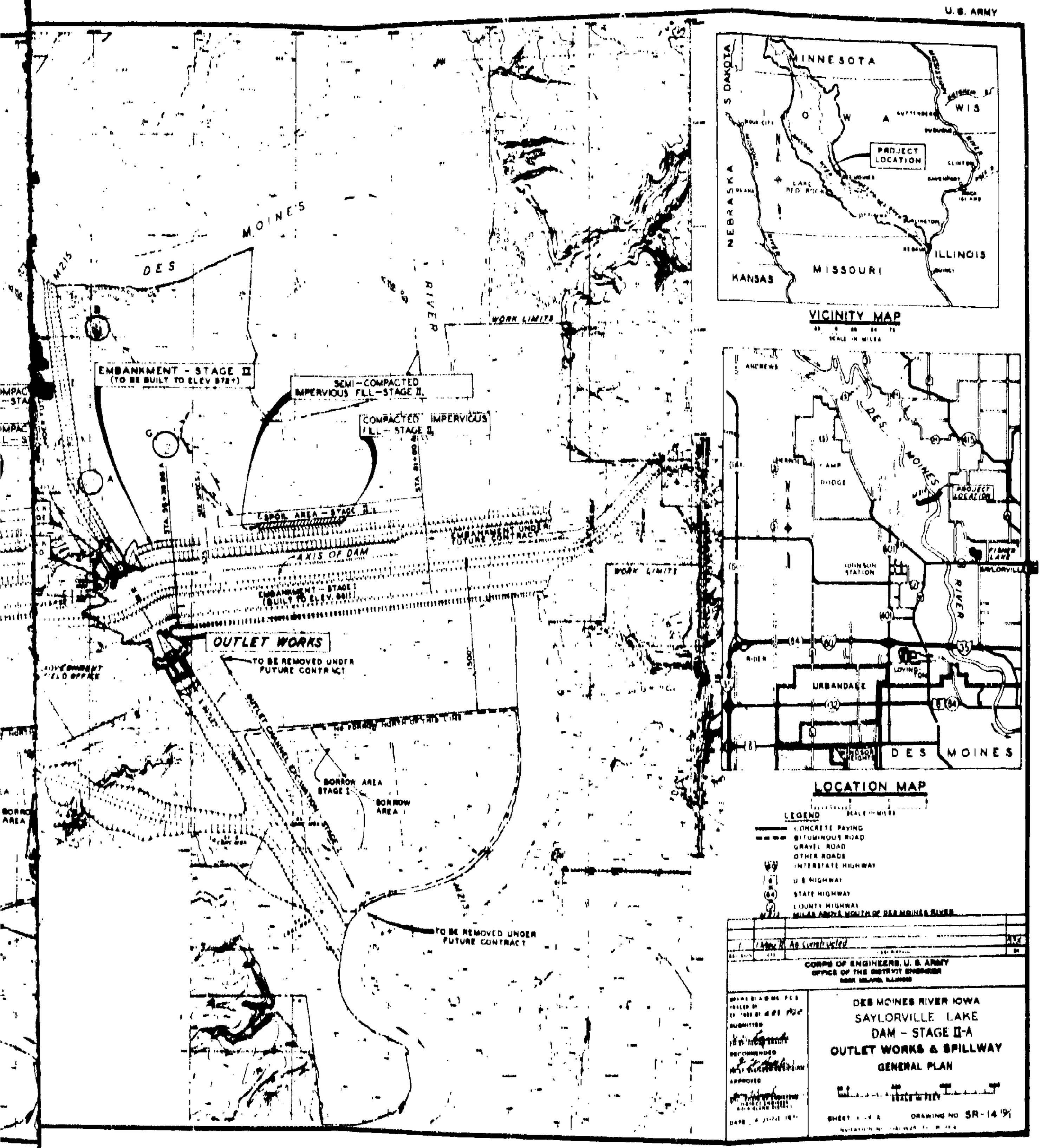


Figure 3. General plan, outlet works, and spi



llwa[neral plan, outlet works, and spillway, Saylorville Lake Dam

18. The emergency spillway is an uncontrolled gravity concrete ogee weir (430 ft wide) flanked with gravity bulkhead sections, 200 ft of paved chute, and approximately 5,000 ft of unlined trapezoidal chute (US Army Engineer District, Rock Island 1962). The engineering design details, topography, and locations of borings and cross sections are illustrated in Figures 4-6. Located in a small valley, the spillway and discharge channel follow an old stream course throughout most of its length.

19. Geology. The unlined spillway channel is underlain by gently dipping, indurated shales, calcareous siltstones, thin limestones, coals, and sandstones which are part of the Cherokee Group of the Lower Pennsylvanian Des Moines Series. In the indurated units (such as the sandstones, the siltstones, and the limestones) jointing (with spacings of 4 to 5 ft and with northeast to southwest, northwest to southeast, and east to west orientations) is the predominant structural discontinuity. Figures 7 and 8 are detailed geologic profiles of the spillway geology before and after the flood event. These profiles show the overall thin to medium bedded nature of the strata and, more significantly, a stratigraphic pinchout of the hard medium-bedded sandstone forming the floor of the spillway between the spillway weir and the centerline sta 11+00.

20. Overlying unconsolidated glacial and aeolian deposits of the Pleistocene Age flank the spillway channel both to the east and to the west. To the east, a hill of these unconsolidated sediments separates the spillway from the west end of the dam embankment.

21. Overflow event. District hydrologists estimate the events producing spillway flow were sustained high flows amounting to a 100-year volume flood along with flows peaking at a 10-year flow frequency. Peak flow (17,000 cfs) and velocities (approximately 7.5 fps) on the upper spillway channel occurred on 22 June, 4-1/2 days after the overflow commenced (Figure 9). At maximum flow, water moved over the weir crest under a head of 5.2 ft. According to the NCR report (US Army Engineer District, Rock Island 1984), total outflows from Saylorville Reservoir were regulated by adjusting the releases from the outlet conduit, and erosion occurred essentially as predicted. The estimated erosion, for flows greater than 20,000 cfs, still remains a prediction with little observed experience.

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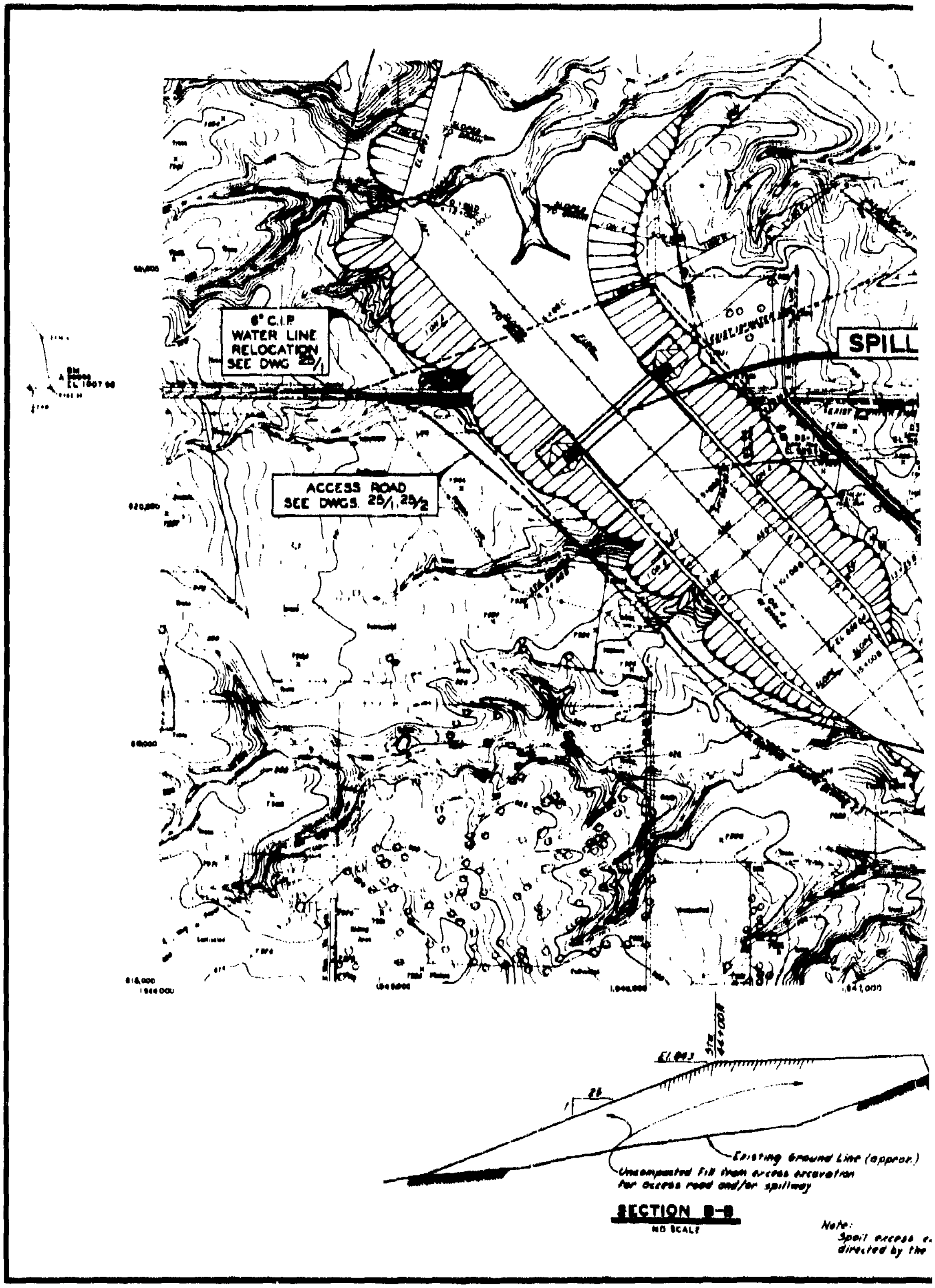
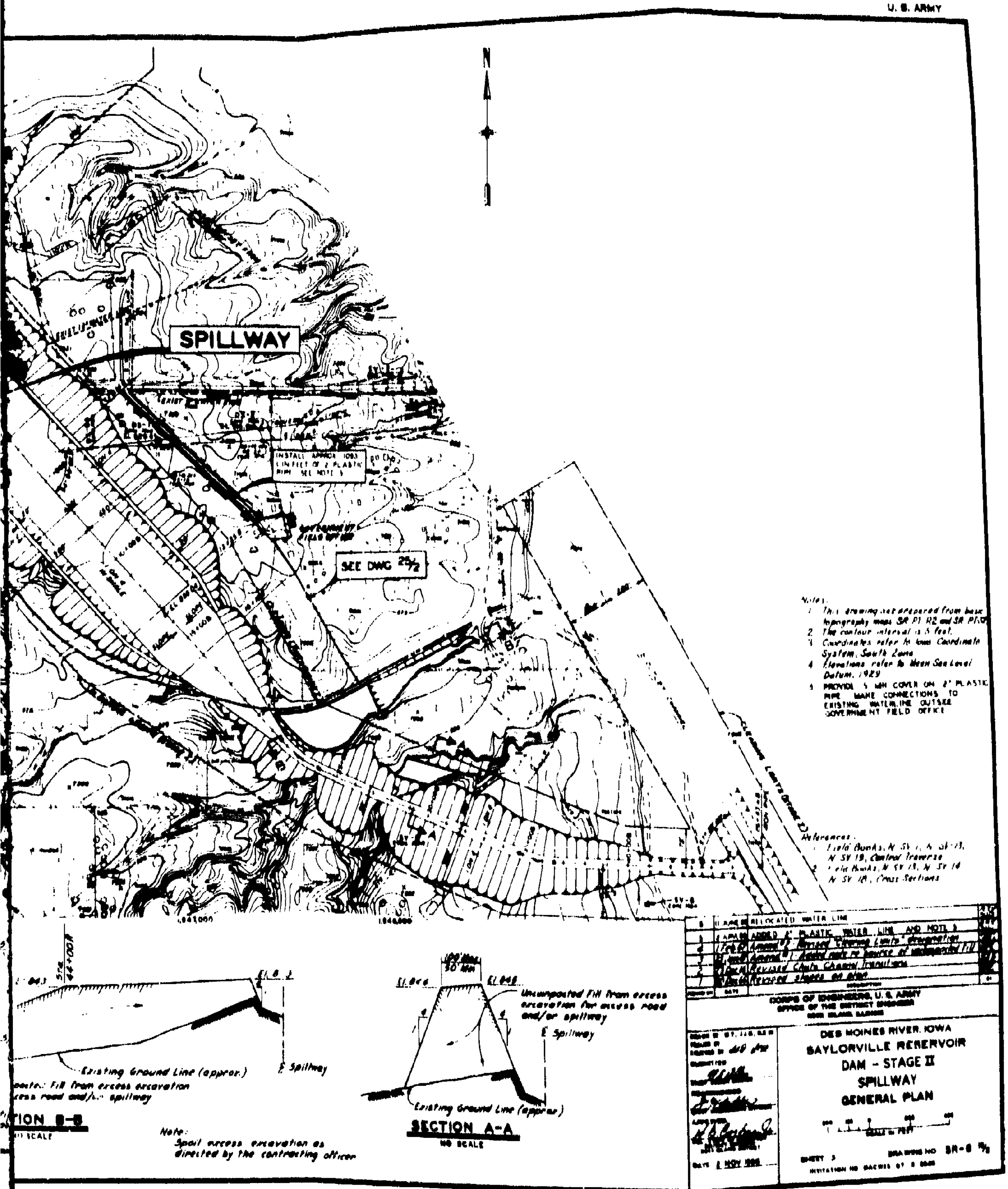


Figure 4. General plan of spil



. General plan of spillway, Saylorville Lake Dam

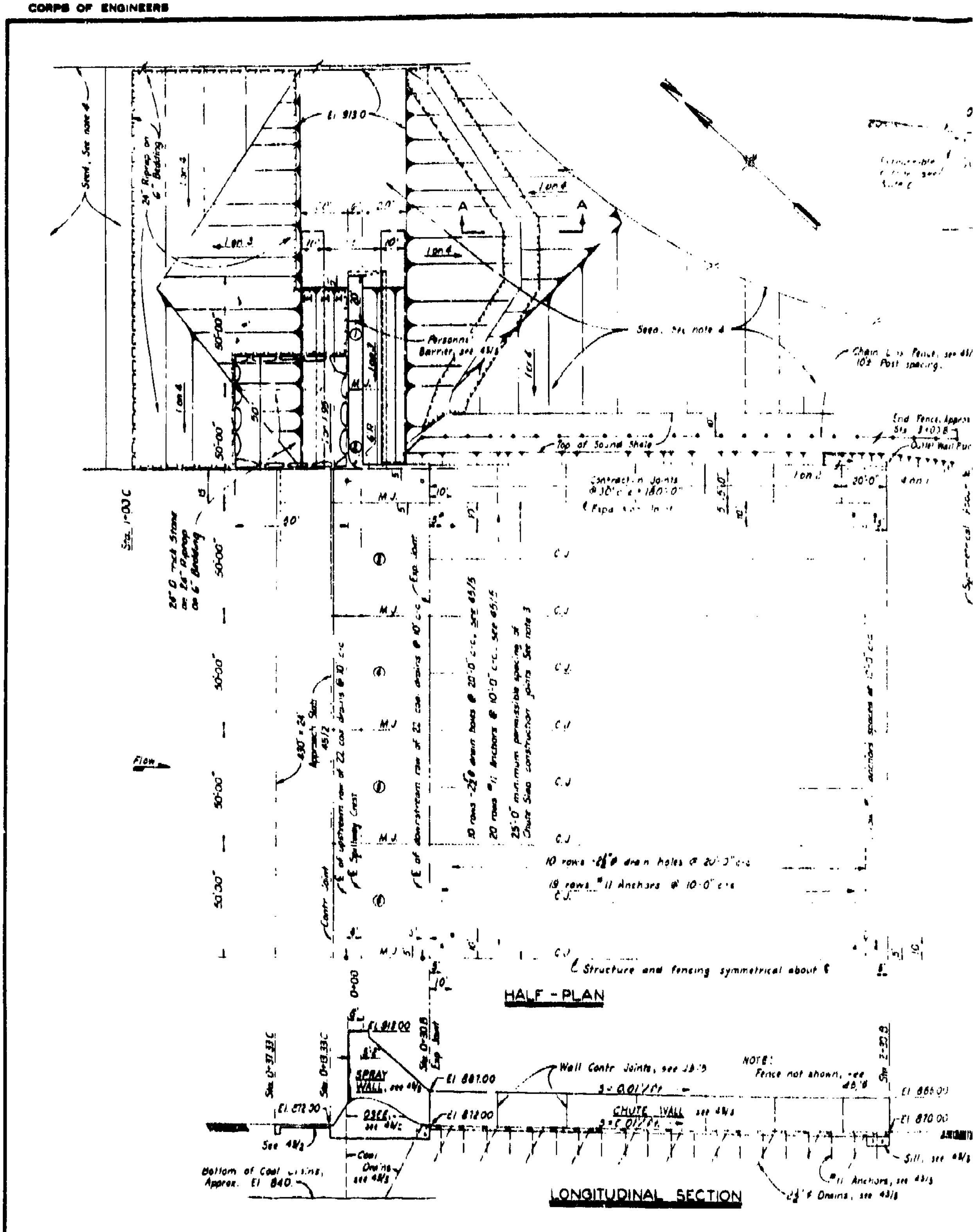
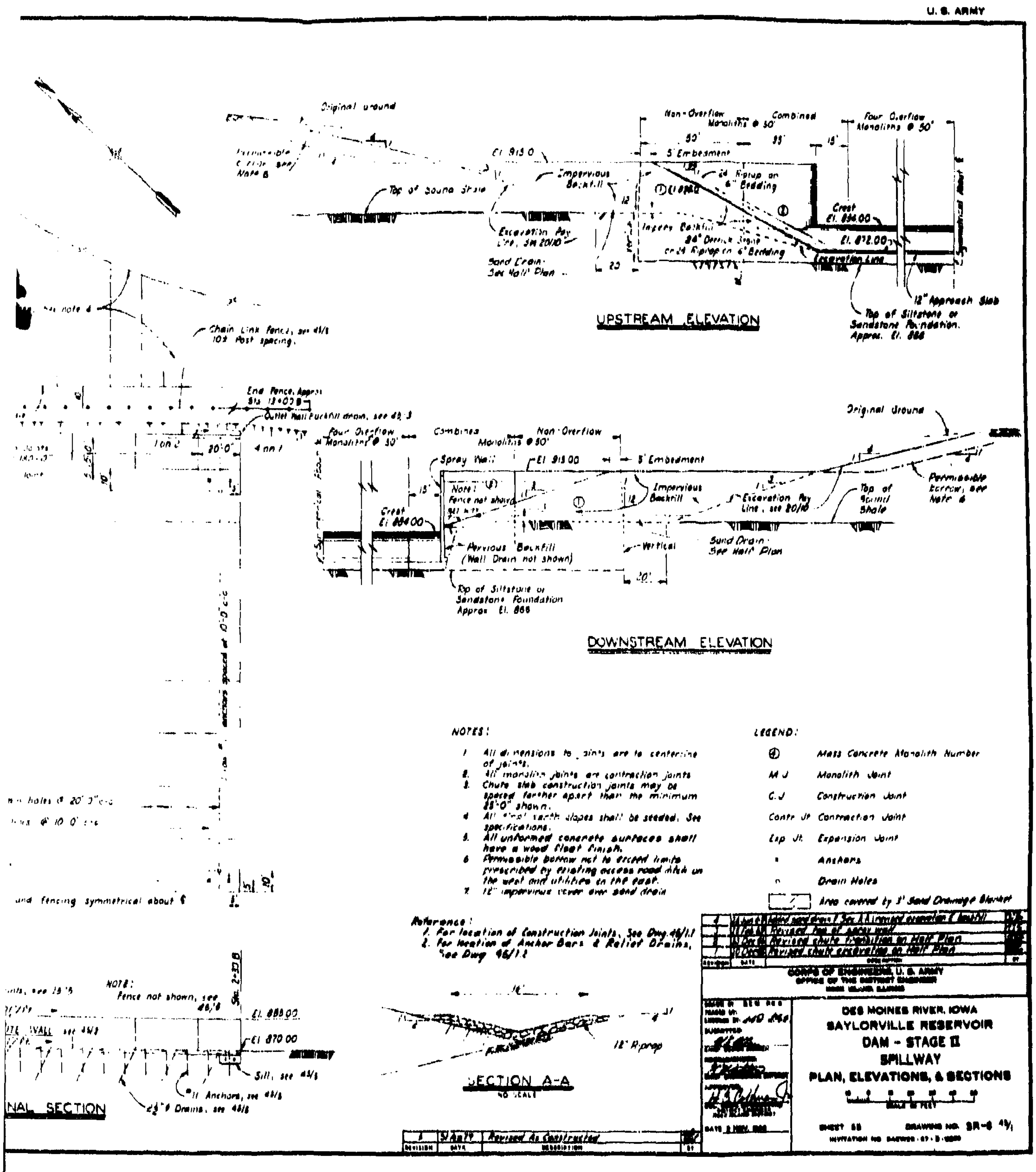


Figure 5. Spillway plan, elevations, and sec



...lway plan, elevations, and sections, Saylorville Lake Dam

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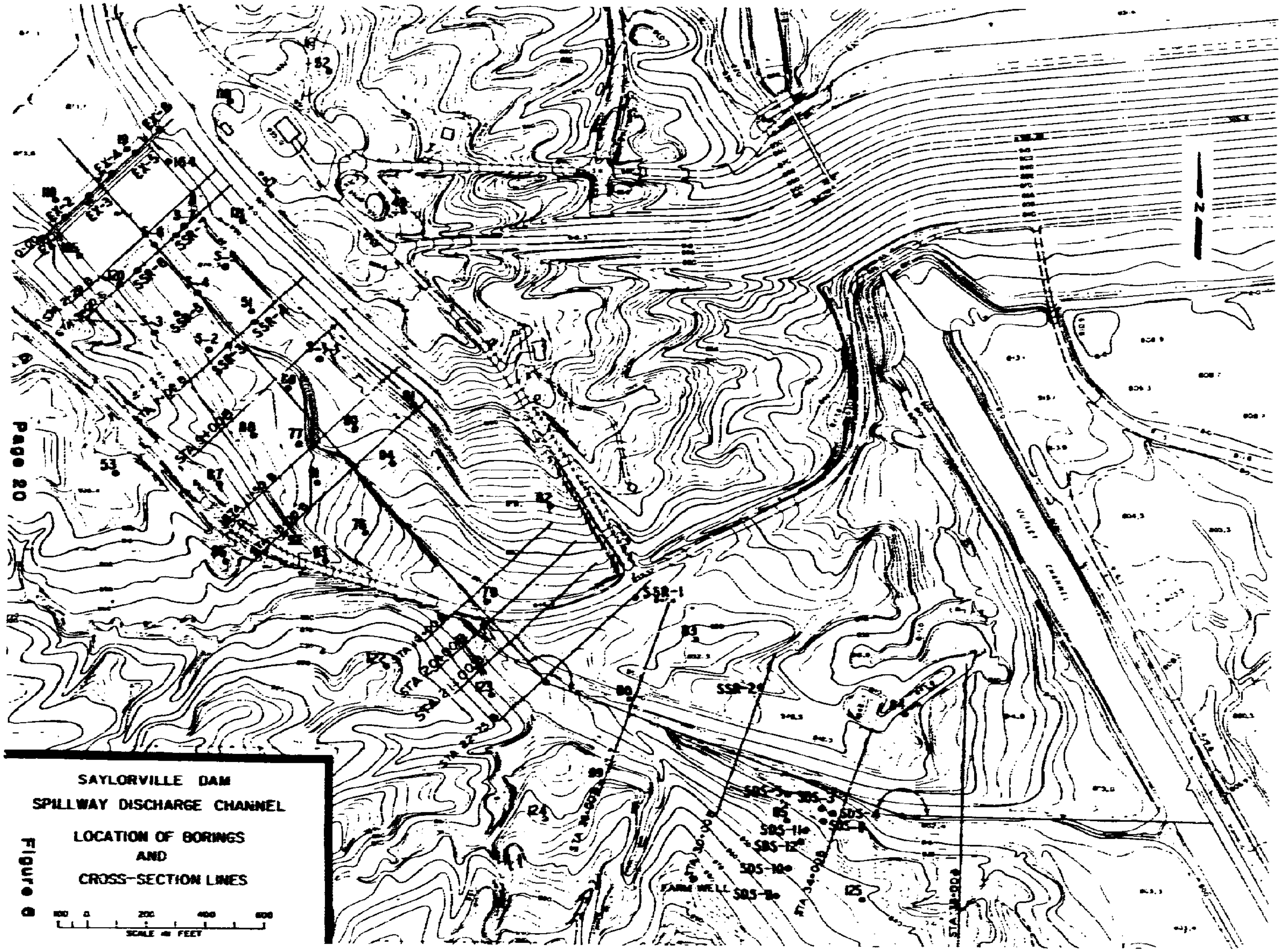


Figure 6. Saylorville Lake Dam. Locations of borings and cross-section lines, spillway discharge channel

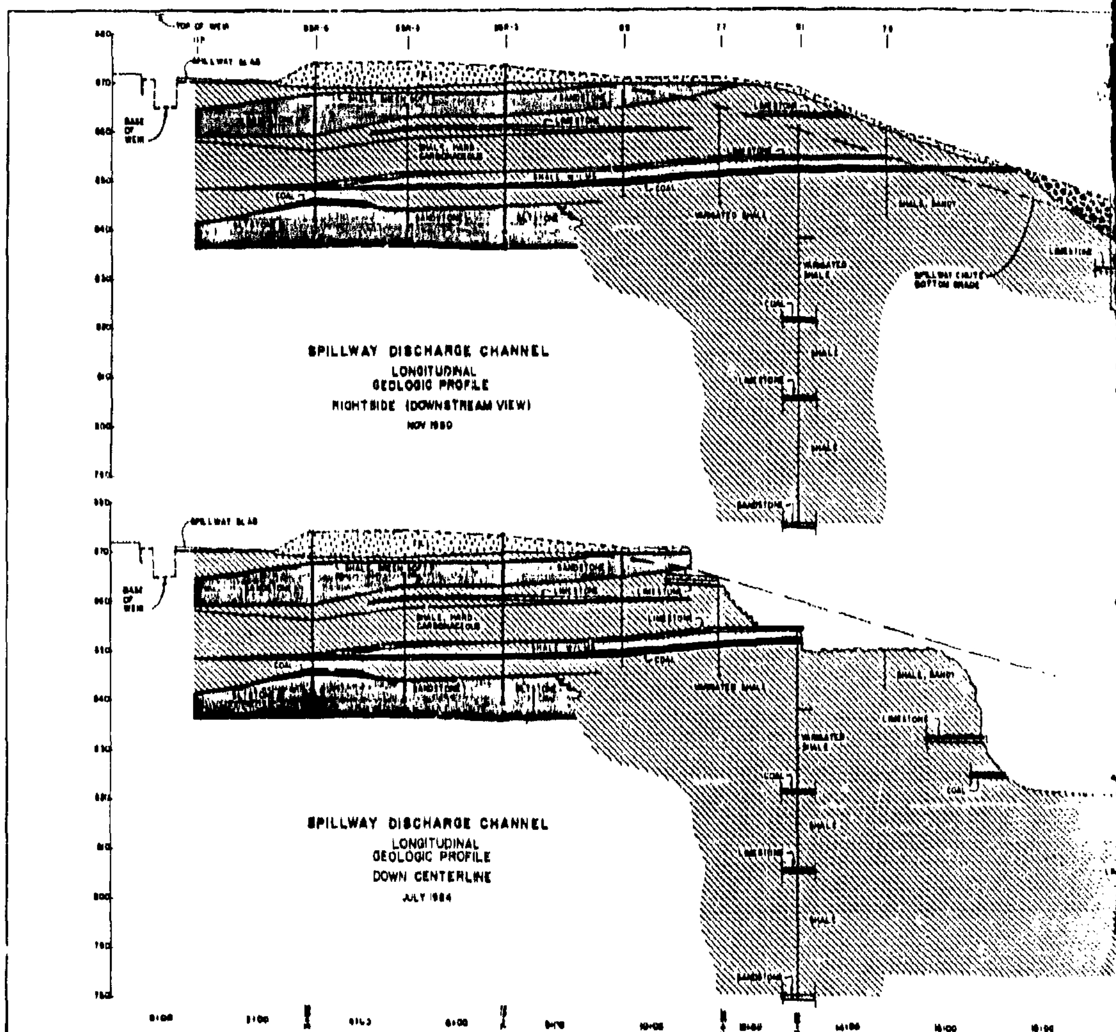
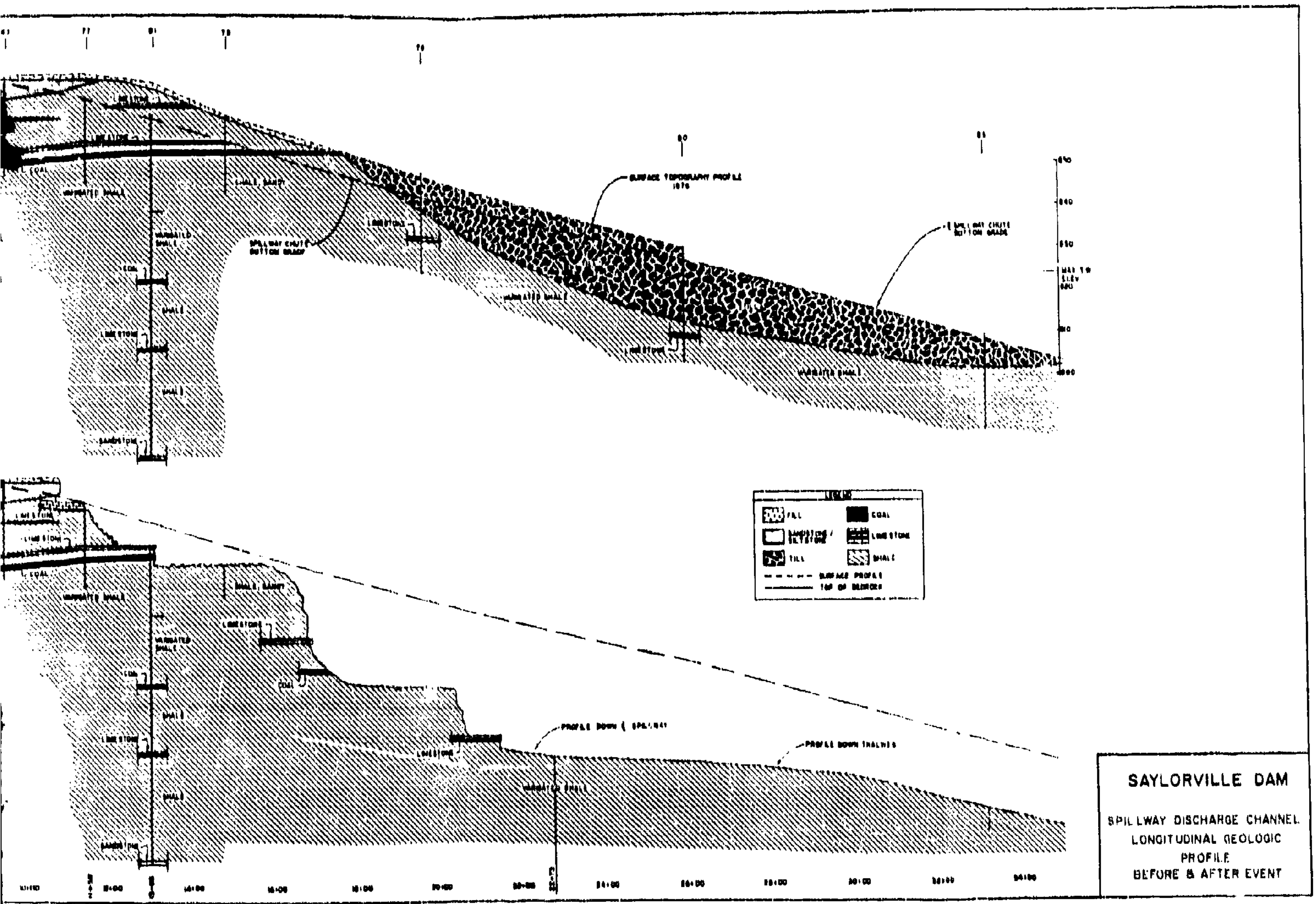


Figure 7. Saylorville emergency spillway dischar
(down centerline) before and afte



lorville emergency spillway discharge channel, longitudinal geological profiles (down centerline) before and after initial spillway overflow.

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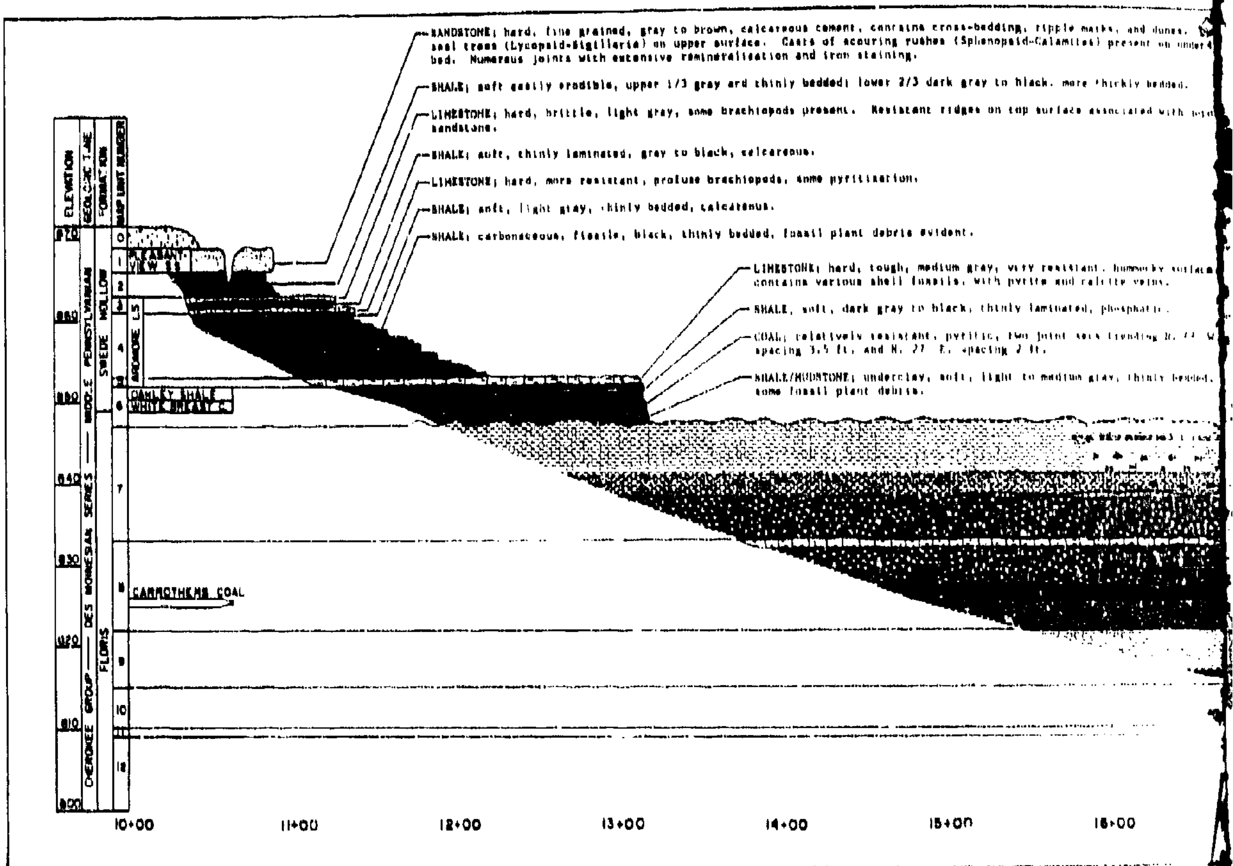
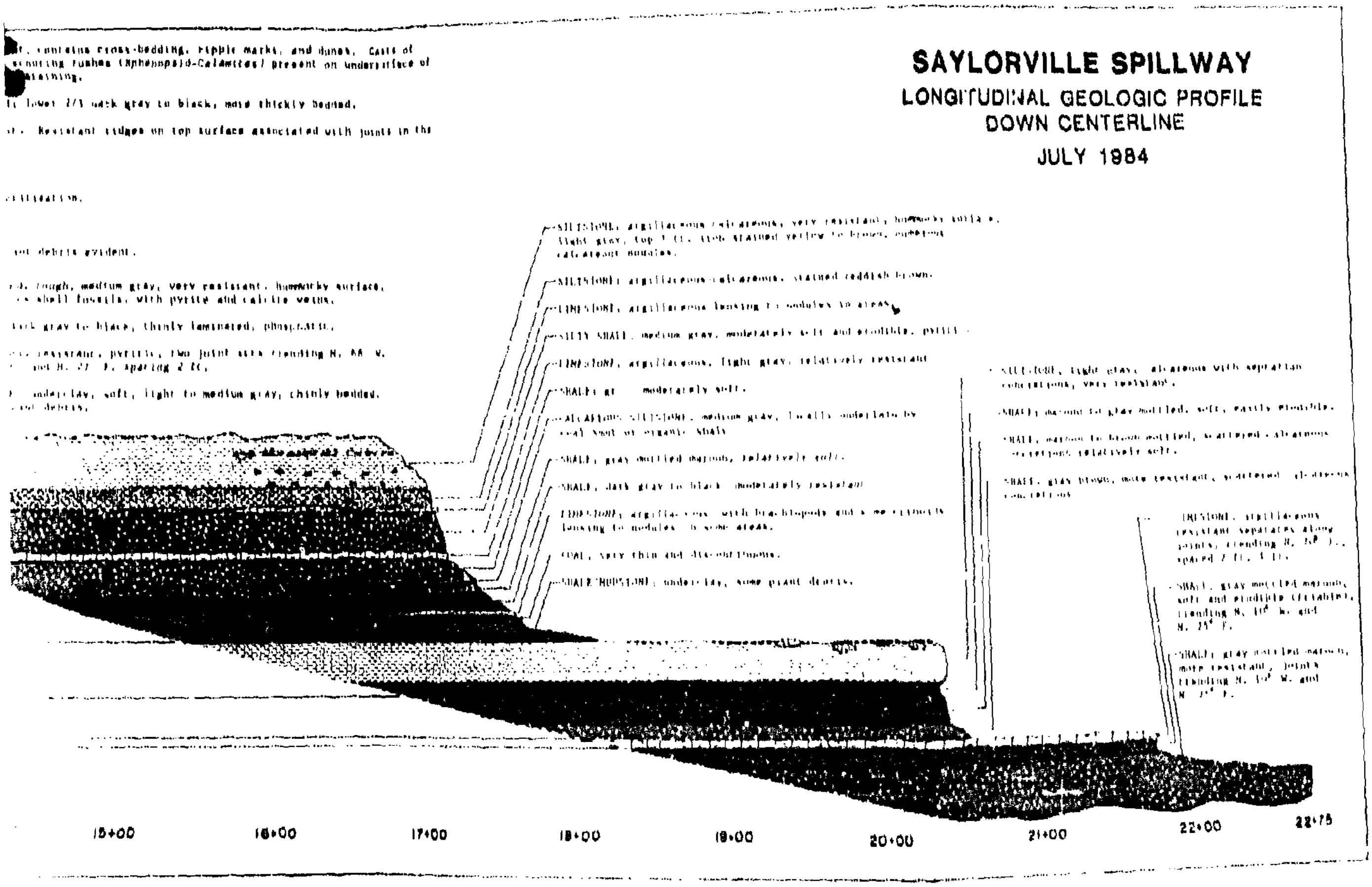


Figure 8. Detailed stratigraphy and litholog
the Saylorville Dam emergency spil



stratigraphy and lithologies underlying the lower portion of
rvillc Dam emergency spillway discharge channel

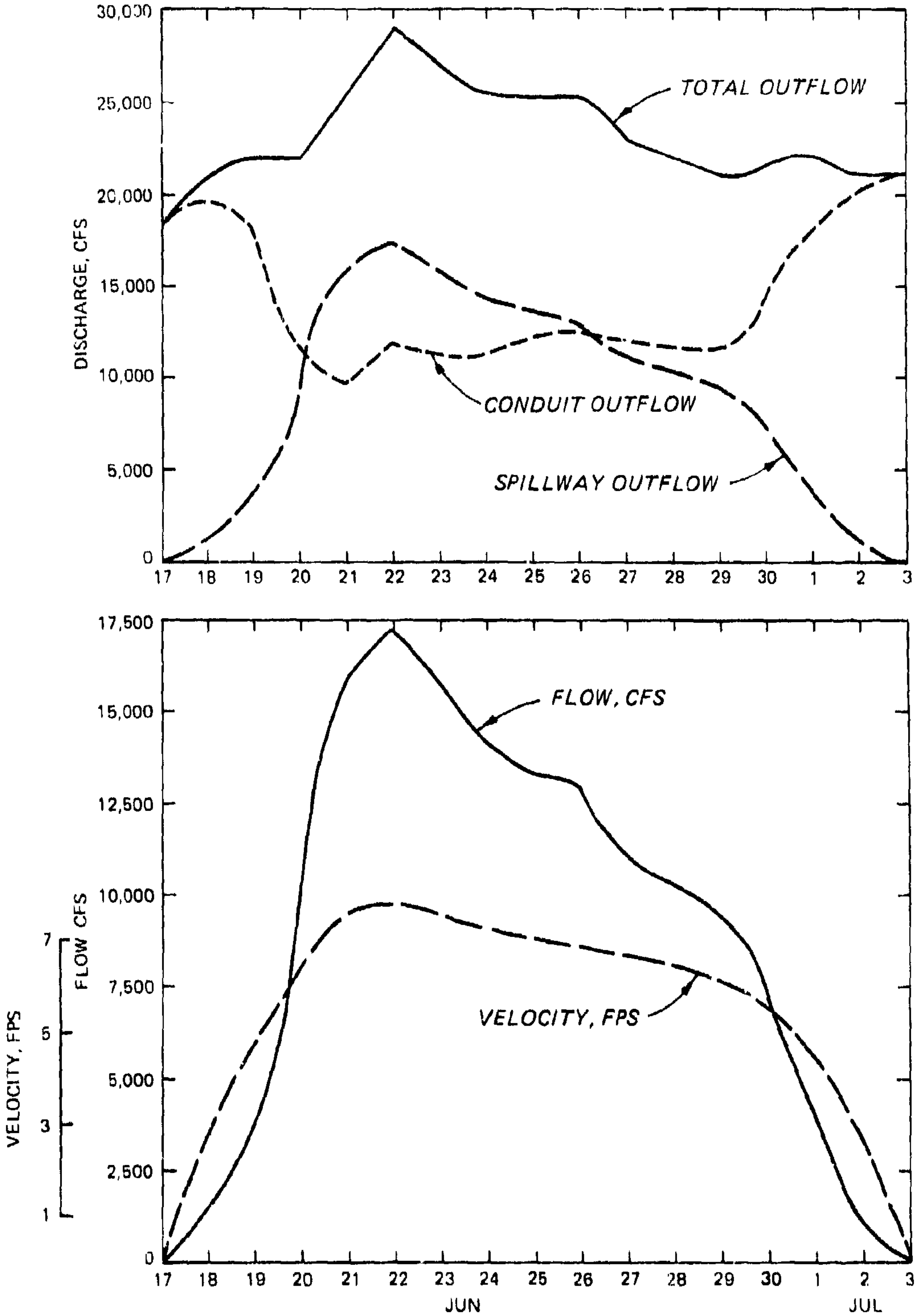


Figure 9. Saylorville spillway, outflow and velocity (at sta 7+00) versus duration of 1984 overflow event

22. Spillway channel erosion. The in-depth study (US Army Engineer District, Rock Island 1962) estimated probable limits of erosion (for flows up to 20,000 cfs) as follows:

> Limits of Erosion. Erosion of the spillway discharge channel will occur within bounds defined by the physical parameters of the geology and available energy determined by the hydraulics. The upper reaches of the channel underlain by hard well-cemented sandstone/ siltstone are nonerodible up to maximum flows of 100-year discharges. The maximum depth of erosion and scour of the shale from Sta. 11+50 to the river will be controlled by the tail-water elevation of the outlet works discharge.
>
> Erosion between the Sta. 11+50 and 19+00 is likely to be limited to topsoil and upper layers of weathered shale. Below this, the shale is hard, calcareous, and inter-bedded with limestone. Tractive shear and uplift forces are relatively low and a bench or terrace may form from the edge of the limestone at Sta. 14 to 19+00 at elevation 853.
>
> Turbulent tractive shear and uplift forces jump to maxi-mum values at Sta.19+00. Scour will be deepest in this area, possibly eroding a hole. As shown on geologic pro-files the bedrock consists of a couple of feet of hard calcareous shale underlain by softer varigated shale. At maximum discharge from the outlet works, the tailwater elevation would be 824 and erosion would continue to Sta.26(+/-) where the rock is overlain by about 18 feet of glacial till. Another large scour hole would be eroded at this point where a critical jump forms.

23. Emergency spillway overflow, which peaked at 17,000 cfs on 22 June 1984, produced the rock erosion predicted by the District's studies of 1981-82. District personnel observed the flow and erosion during the event as well as examined the before and after flood longitudinal geologic profiles (see Figure 7), and sections comparing preflood and postflood topography at twelve locations in the channel (Figures 10-12) revealed the following:

a. Subcritical, nonerosive flow which only removed part of a thin grass and topsoil veneer over the bedrock was maintained to sta 11+50. District personnel estimated flow velocities in this portion of the channel were in the range of 7 to 10 fps. Stability of this portion of the channel was maintained by the continuous, hard, scour-resistant, medium-bedded sandstone which forms the channel floor to this point.

b. The stratigraphic pinchout of this sandstone in the vicinity of sta 11+50 probably controlled the position of a gradient change

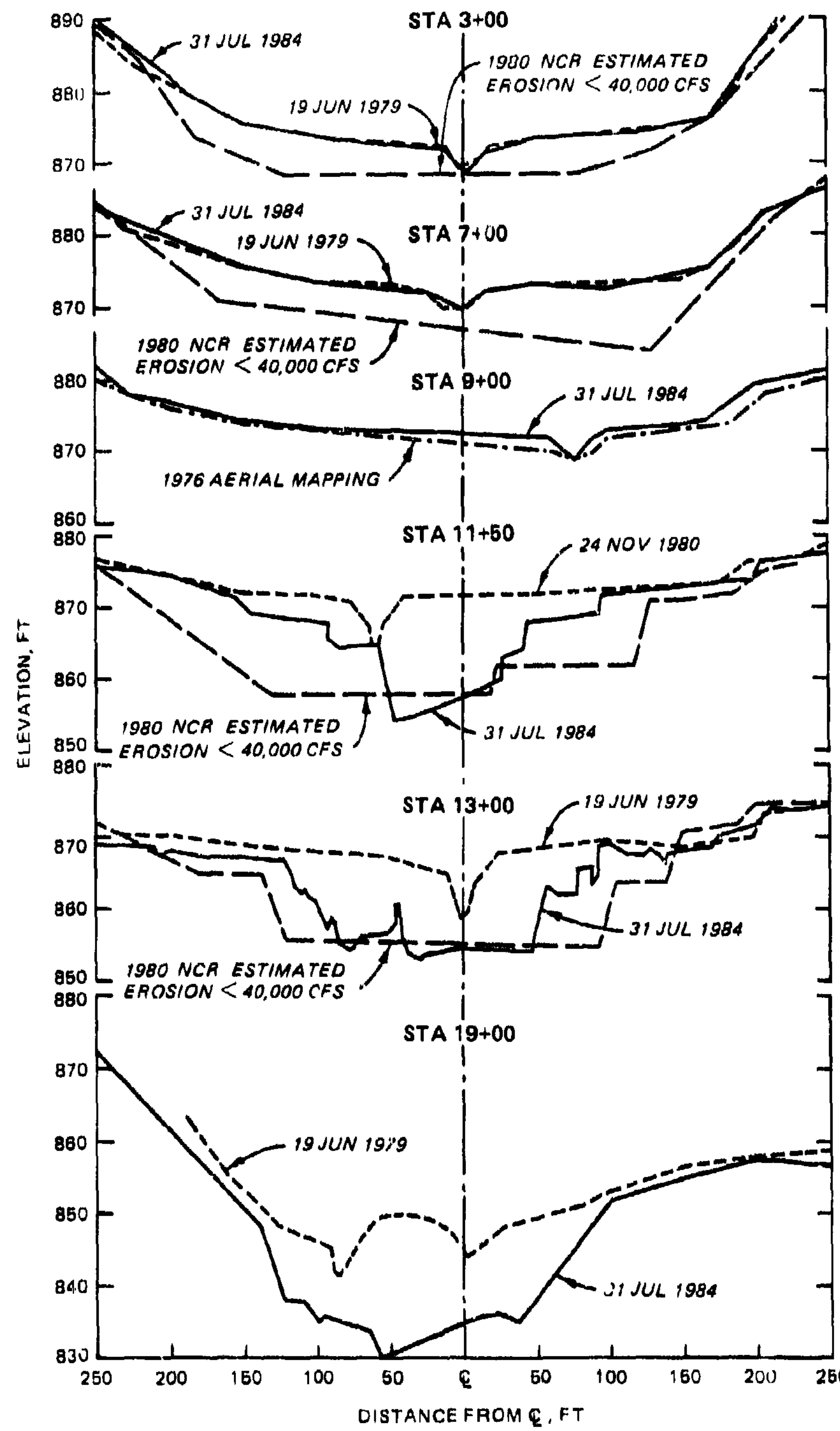


Figure 10. Saylorville emergency spillway discharge channel, cross sections from sta 3+00 to sta 19+00 showing preflood and postflood topography and the 1980 NCR erosion estimates for overflows less than 40,000 cfs

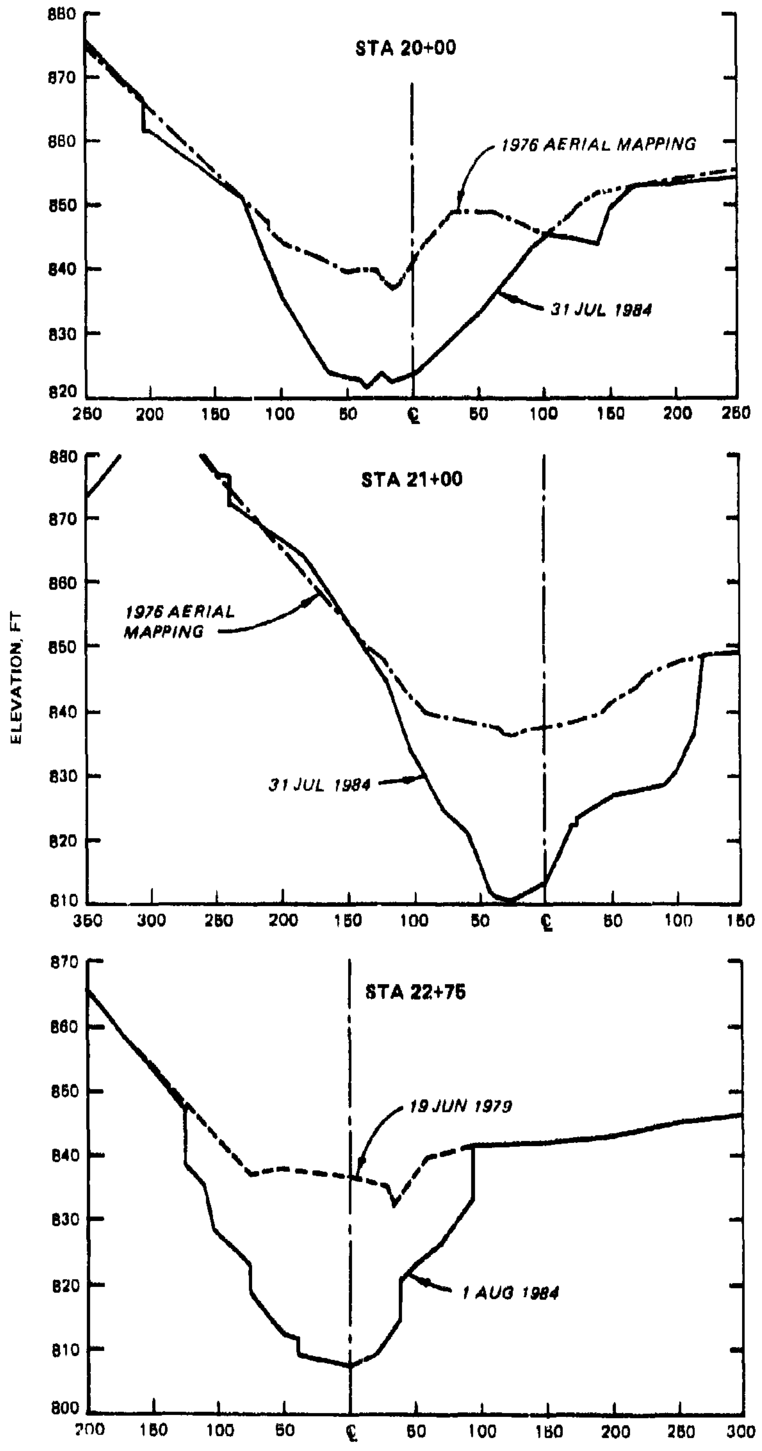


Figure 11. Saylorville emergency spillway discharge channel, cross sections showing preflood and postflood topography

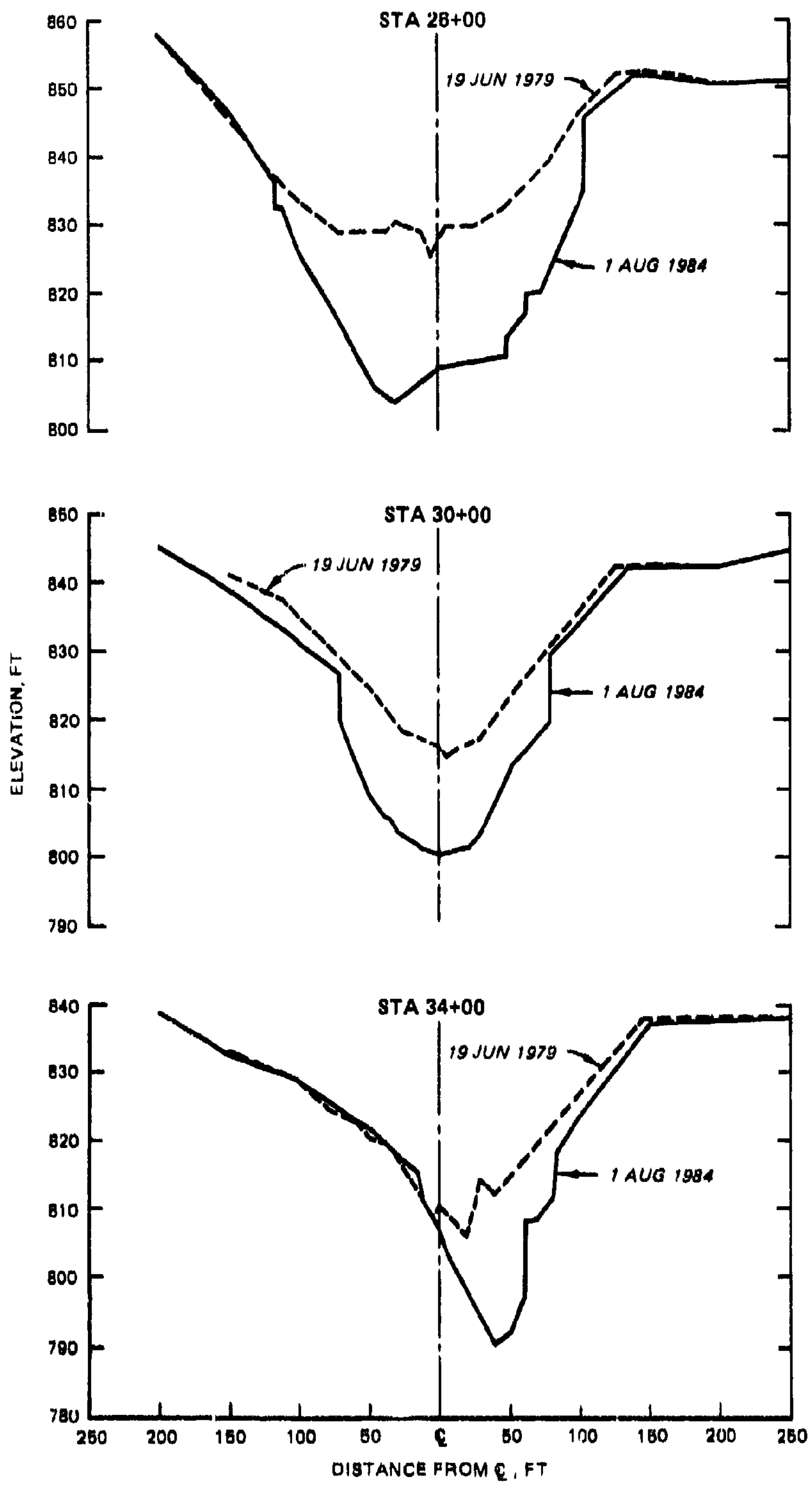


Figure 12. Saylorville emergency spillway discharge channel, cross sections showing preflood and postflood topography

(knickpoint*) in the preflood channel. Downstream from this position, the flow velocity increased and, by the third day, the turbulent white-water flow created falls between sta 10+90 and sta 11+50. Estimates by District personnel of the turbulent flow velocity below the falls area were in the 20- to 25-fps range.

c. Downstream from the falls this flow (estimates range as high as 40 fps) preferentially eroded softer, less resistant units (particularly shales) and formed a series of scour pools and cascades as the flow (and its velocity) increased during the third, fourth, and part of the fifth day. Continued overflow for another 10 days left erosion scars and scour pools as deep as 30 ft in downstream portions of the channel (Figures 13 and 14).

d. Channel curvature between sta 19+00 and sta 23+00, where an access road was breached at the onset of spillway overflow, resulted in switchbacks and flow deflections at various locations along the downstream channel. The left bank near sta 21+00 was initially eroded more than the right bank because of uneven flow through the breached access road. This situation apparently reversed with time. By June 28 thalweg migration and deepening between sta 20+00 and sta 23+00 resulted in oversteepening of the right bank (which consisted of unconsolidated glacial deposits), and a slide developed.

24. Other impacts. As indicated above, channel degradation and migration caused a portion of the right spillway channel bank to oversteepen and slump (Figure 15). The District report expresses some concern that a future flow might erode the bank to the point where major slope failure could occur and in the process dam the spillway discharge channel. Such an event could conceivably result in the flow being redirected into preconstruction drainage paths and even toward the outlet works and the downstream toe of the dam.

25. The initial flow of the Saylorville spillway resulted in the removal of approximately 500,000 tons of rock and soils from the channel. Postflood surveys demonstrated that some of these materials were deposited as a

---

* Knickpoint: A point of abrupt change or inflection in a stream profile, (AGI 1972). Knickpoints can migrate headward when they are sufficiently steep and are undercut by severe scour. In gently dipping stratified sedimentary rock sequences of alternating lithologies (sandstones, siltstones, shales, siltstones, etc.), several steep knickpoints can develop and produce a series of steps and benches with knickpoints often migrating headward at variable rates. This erosion pattern resembles "stairsteps" of varying symmetry in longitudinal profile. The eroded profile of the unlined portion of the Saylorville spillway is a classic representation of this type of erosion. In this report "knickpoint erosion" and "headcutting" are used synonymously unless otherwise stated.

Figure 13. Downstream view of the severe erosion that occurred in the unstable portion of the Saylorville emergency spillway discharge channel during the 1984 overflow

Figure 14. An upstream view of the Saylorville spillway discharge channel illustrating the "stair-step" erosional pattern exhibiting almost 30 ft of local relief

Figure 15. Portions of the right bank of the Saylorville emergency spillway discharge channel that were undermined by severe channel scour during the 1984 overflow event. Slope failure occurred shortly thereafter

rocky delta where the spillway discharged into the Des Moines River and as a sand bar which formed approximately 1 mile downstream from the dam. The survey results indicated that most of the material lost from the spillway was deposited at points further than 4 miles downstream from the dam.

26. The high flows of 18 June to 4 July 1984 definitely resulted in the erosion of the right bank of the Des Moines River approximately 2 miles downstream from the dam. This erosion resulted from both spillway and outlet-works discharges during the flood event.

27. Remedial and preventive action. The District report's evaluation of the initial overflow concluded that recurring overflows of less than 20,000 cfs (occurring at a frequency of once in 18 to 100 years) can be passed by the Saylorville spillway without endangering the structure or facility safety. Alternatives for remedial construction were (a) refilling and revegitating the entire eroded canyon, (b) slope stabilization between sta 21+00 to about sta 34+00, (c) hardening at selected locations to prevent surface sandstone from uplift during large magnitude floods approaching the SDF, and (d) maintaining the unprecedented exposures (for Iowa) of Pennsylvanian Period

bedrock as an "interpretive resource." After examining these alternatives, the District recommended the following measures:

a. Smooth, fill, and seed all irregularities in the sod-covered reach of the flat channel between sta 2+30 and sta 10+00 to maintain the erosion resistant grass and soil cover. Do the same for the reach between sta 13+00 and sta 17+00.

b. Fill the upper end of the erosion gully between sta 10+00 and sta 12+00 with lean concrete and form a cusp for control of erosion at the downstream end of the flat portion of the channel.

c. Fill the upper end of the erosion gully at sta 17+00 with lean concrete to reduce erosion at the downstream end of the siltstone.

28. The District also noted that for flows greater that 20,000 cfs, experience records are not available to accurately predict the erosion of rock in the spillway channel and suggested the following actions for future investigations:

a. Evaluate by a model study the uplift and erosion resistance of blocky sandstone when subjected to supercritical velocities and hydraulic jumps at various locations in the channel beyond the chute slab.

b. Formulate a plan to provide rock anchoring beyond the chute slab that would ensure stability of the ogee structure.

Lake Brownwood spillway

29. Background information. The Lake Brownwood Dam is located at mile 57.1 on Pecan Bayou, a tributary of the Colorado River, about 8 miles north of Brownwood, Texas (Figure 16). The Lake Brownwood Dam is not a CE project; however, the CE was authorized by the Flood Control Act of 1968 to provide technical support to modify the dam and to repair the unlined spillway channel which has suffered considerable erosion in three floods during and since impoundment of the reservoir in 1932. No modifications or remedial actions have taken place at the project to date. The no-action plan in effect will allow headcutting to continue during future spillway overflows. If headcutting in the spillway channel continues at the same rate as in the past 54 years, the eroded section will reach the concrete sill control section in 100 years. If the sill were to be undermined and to fail, there would still be about 1,000 ft more of the progressive erosion before it reached a point of total breach.

30. The total Pecan Bayou drainage area contains 2,202 square miles, 1,544 of which is above the US Geological Survey (USGS) Gage 430 at the Lake

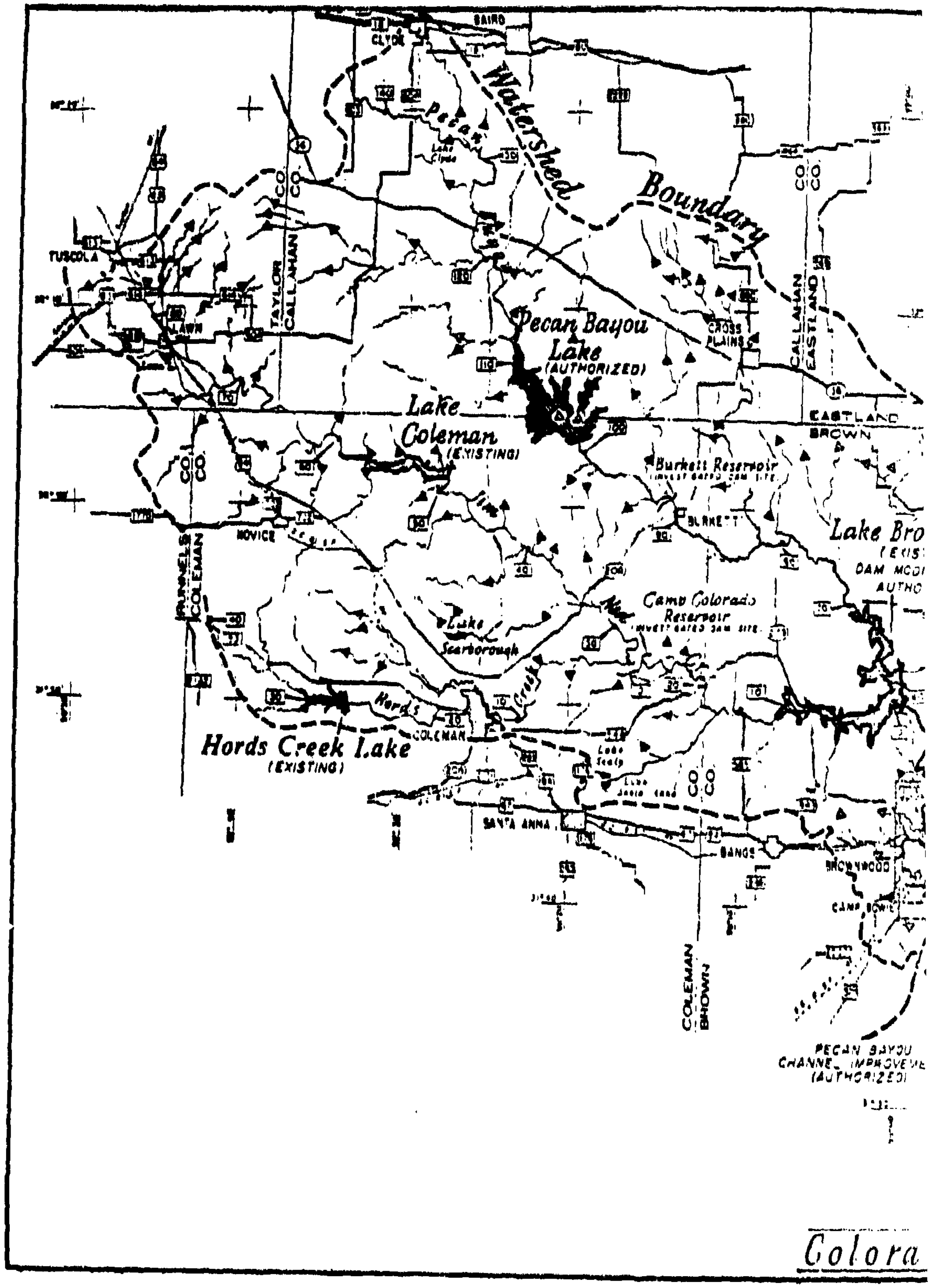


Figure 16. Watershed map,

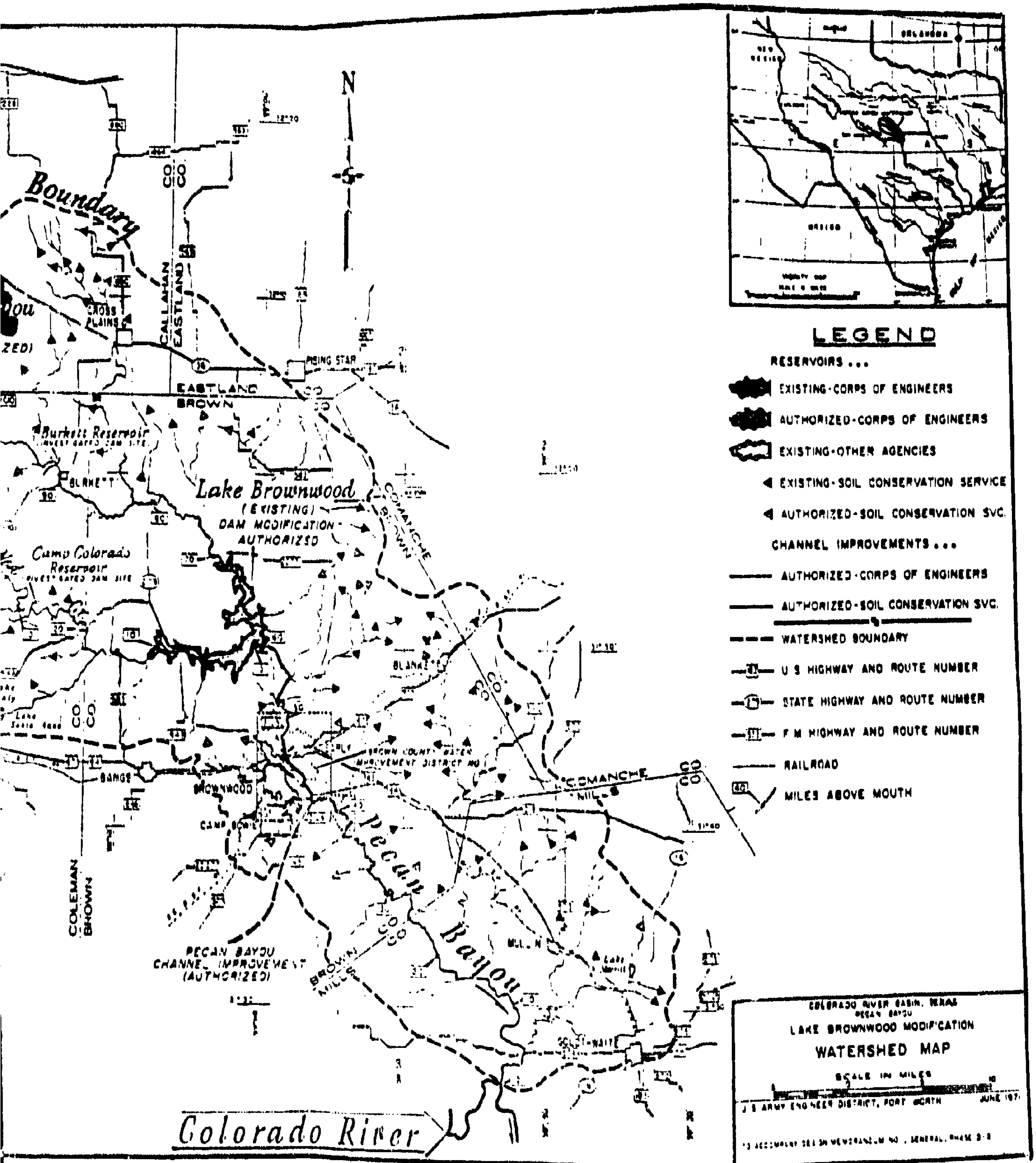


Figure 16. Watershed map, Lake Brownwood Dam

Brownwood Dam. The region is underlain by nearly flat-lying sedimentary rock strata of the Pennsylvanian and Permian Ages. The topography in the western part of the region is characterized by gently rolling hills and occasional buttes. The damsite and northeastern part of the region are underlain by resistant sedimentary rocks that form escarpments and typically exhibit a more rugged topography. Parallel northeast-southeast ridgelike undulations trend across the damsite. The estimated average annual runoff for the area above the dam for the period 1 January 1924 to 31 December 1970 is 143,000 acre-ft (1.74 in.) with a maximum of 440,500 acre-ft (5.35 in.) and a minimum of 28,000 acre-ft (0.35 in).

31. The Lake Brownwood Dam consists of a rock-filled embankment surrounding an impervious core and is 1,820 ft in length (Figure 17). The top of the dam is at el 1,450 ft with a maximum height above the streambed of 130 ft. The outlet works consists of one 10-ft-diam gate-controlled conduit with two 4-1/2- by 10-ft service gates. The dam was constructed for flood control, irrigation, and municipal and industrial use and is now used for recreation as well. The project, operated by the Brown County Water Improvement District No. 1, began operation in 1932.

32. The Lake Brownwood Dam emergency spillway was constructed during the period 1930 to 1933. The spillway approach channel, located about 800 ft left of the left dam abutment (Figure 17), is about 650 ft long and 470 ft wide with its bottom at el 1,423.0. An uncontrolled broadcrested weir (with a crest el of 1,425, length of 480 ft, and side slopes of 1V on 1.5H to natural ground) is located at the downstream end of the approach channel (Figure 18). The discharge channel is unlined immediately downstream from the weir. The channel has a level grade on a limestone rock ledge at a minimum el of 1,418 for a distance of 316 ft downstream from the weir where the ledge terminates at a sharp knickpoint caused by headcutting during prior spillway overflows. Downstream from this knickpoint the channel cascades over two more steps formed by resistant ledges before entering the tributary to Pecan Bayou at el 1,365, a vertical drop of 54 ft in a horizontal distance of less than a quarter of a mile. The channel knickpoints formed by progressive headcutting during spillway overflows are well illustrated by the spillway channel profiles and longitudinal geologic sections shown in Figures 19 and 20, as well as in Figures 21 and 22 which are recent photos taken in the eroded sections of the channel.

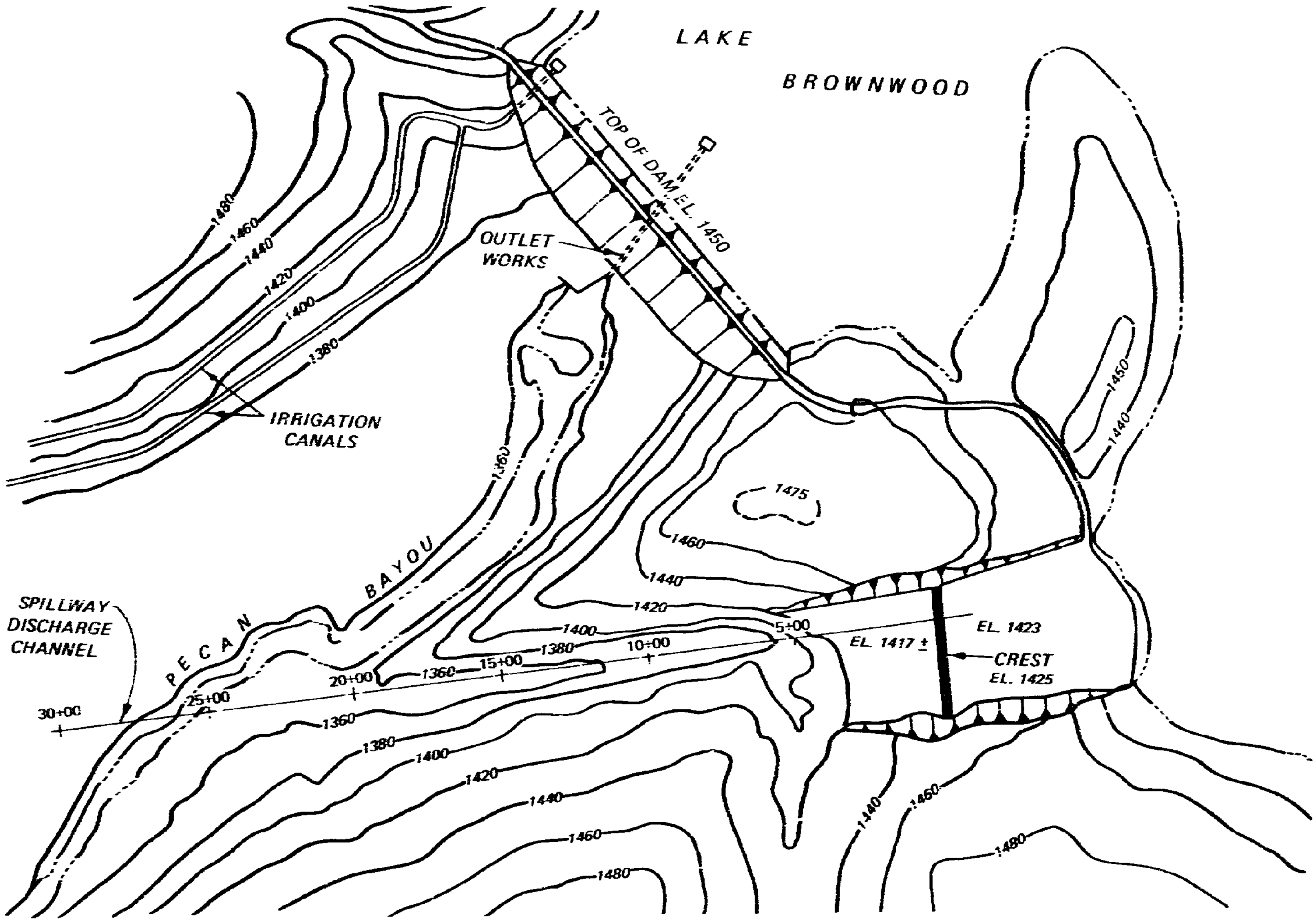


Figure 17. Lake Brownwood Dam. General plan of main embankment, outlet works, and emergency spillway

Figure 18. The Lake Brownwood emergency spillway. The unlined discharge channel is immediately downstream (to the right in this view to the northeast) from the 480-ft-long broadcrested weir

33. The maximum SDF for the Lake Brownwood emergency spillway is 347,000 cfs with the reservoir el of 1,464.7. This flood is based on a maximum precipitation volume of 23.82 in. over a duration of 48 hr, with peak inflow to the full reservoir of 187,700 cfs and maximum outflow of 107,700 cfs.

34. Geology. The area of the Lake Brownwood Dam is underlain by alternating limestones and shales of the Canyon Group (Pennsylvanian) attaining a thickness of 600 ft in the project area. These units are subdivided (from oldest to youngest) into the Graford, Winchell, Brad, and Caddo Creek Formations. The Graford and Winchell Formations are exposed at the damsite. The Grafford Formation is covered in the valley but is well exposed in the lower end of the spillway discharge channel. The formation consists predominantly of soft-to-moderately hard multicolored shales and a 20± ft-thick sandstone bed occurring approximately 20 ft below the base of the overlying Winchell Formation.

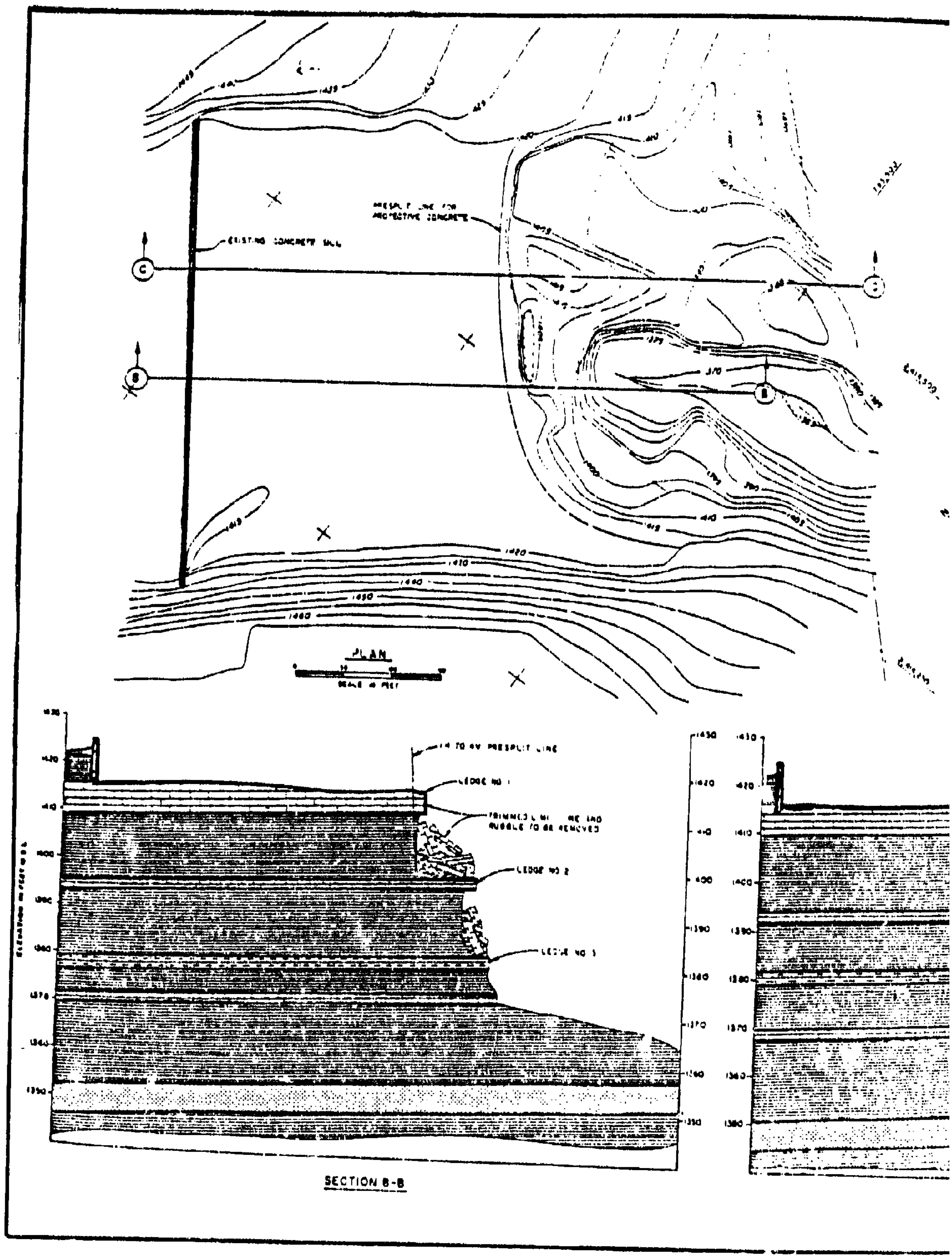
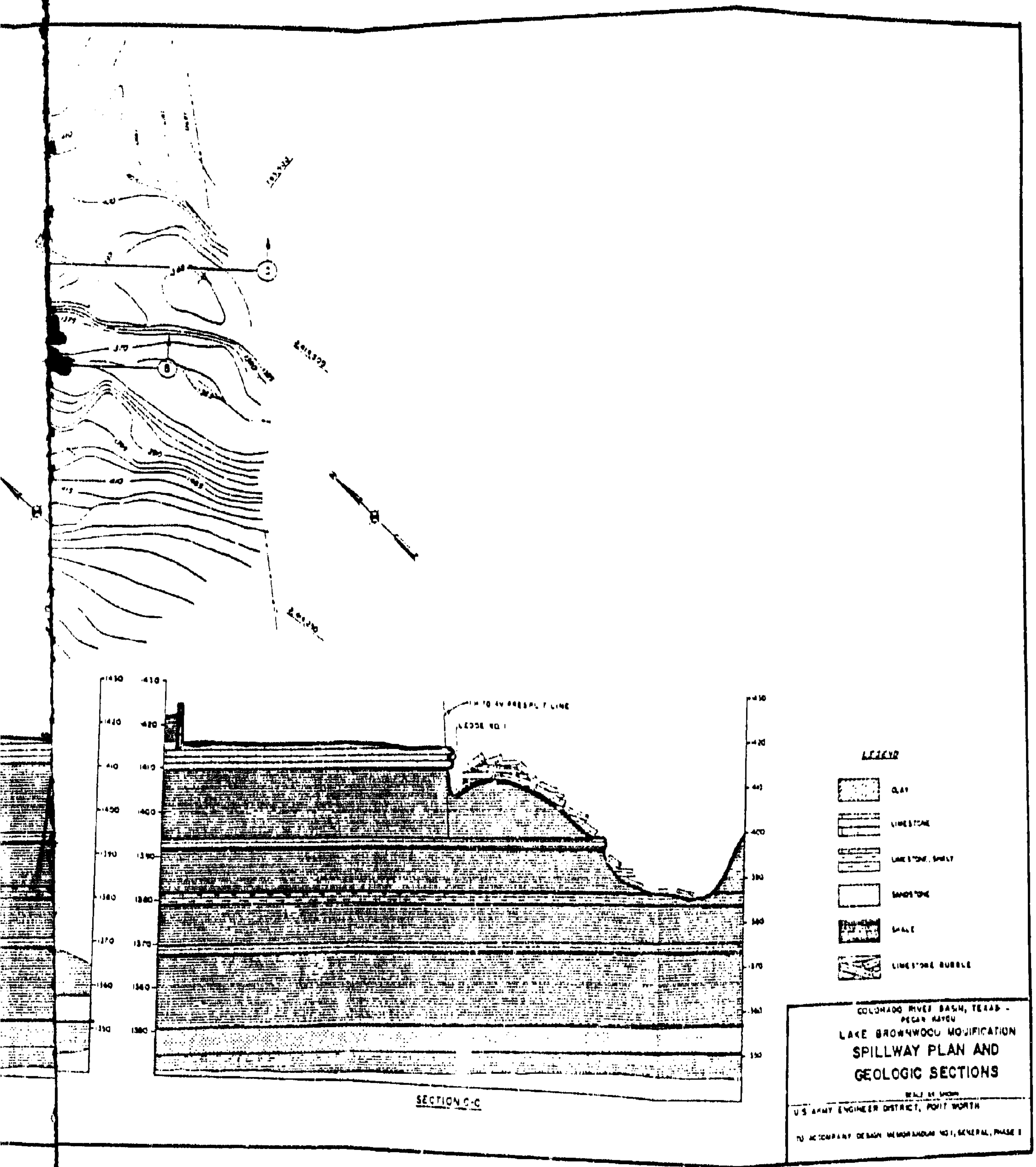


Figure 19. Spillway plan and geologic



sectic Spillway plan and geologic sections, Lake Brownwood Dam

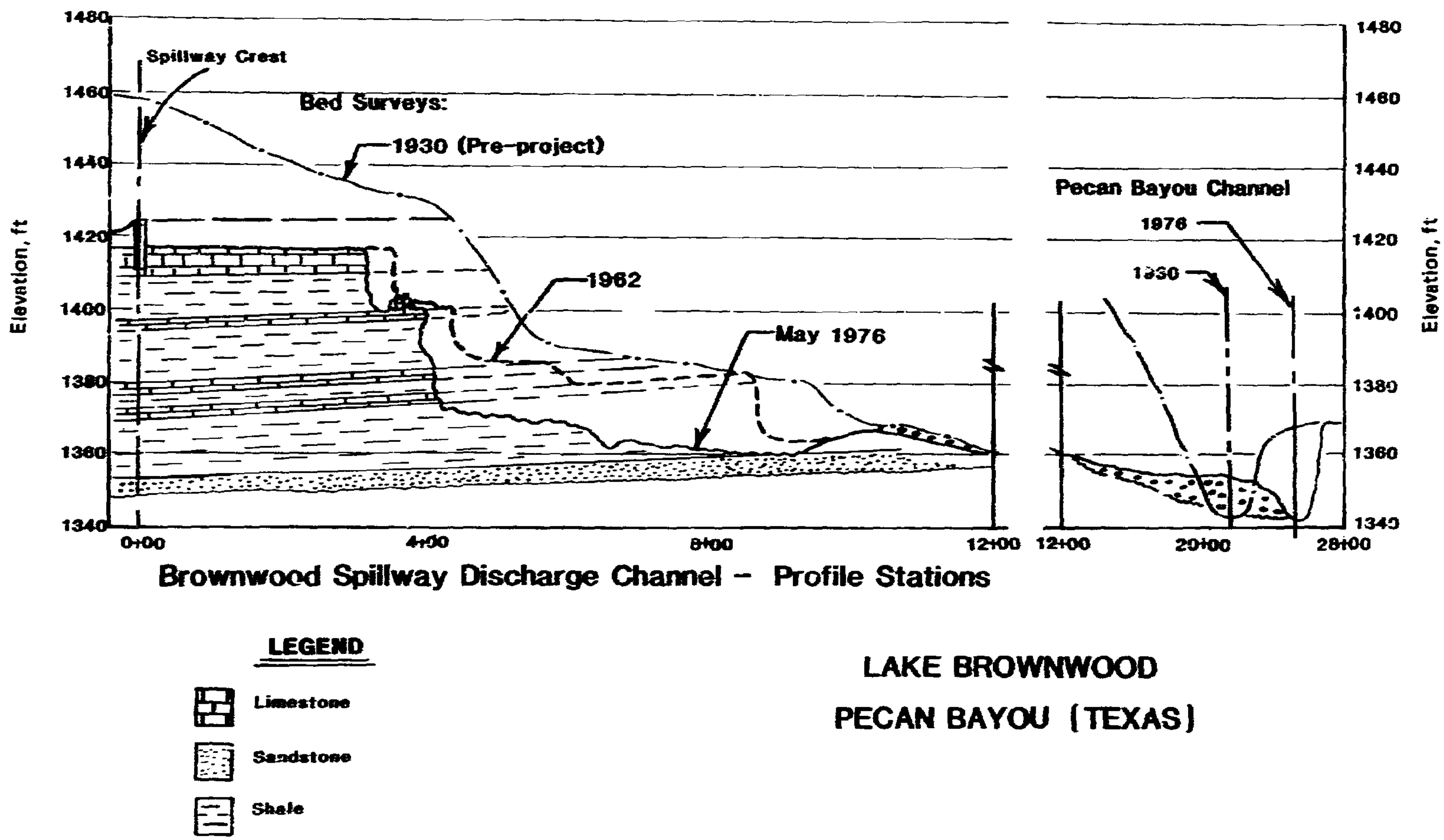


Figure 20. Lake Brownwood Dam. Emergency spillway discharge channel profiles

Figure 21. The Lake Brownwood emergency spillway discharge channel is underlain by a resistant limestone bed which has a level grade to sta 3+16 (shown above to the left). The bed is truncated by erosion at a steep knickpoint caused by headcutting in the unstable portion of the channel during prior spillway overflows

Figure 22. Eroded blocks of limestone are perched on steps formed by headcutting in unstable portions of the Lake Brownwood emergency spillway discharge channel

35. The Winchell Formation is approximately 120 ft thick and contains two resistant limestone sequences each separated by 30 ft of shale with thin sandstone interbeds. In the spillway channel, the lower limestone sequence is 15 ft thick and consists of two limestone units separated by 5 to 8 ft of moderately hard shale. The sedimentary strata in the dam and spillway area dip very gently to the northwest (regional dip is approximately 60 ft/mile) and are apparently unaffected by faulting. Some limestone partings are exposed in the spillway channel. The relative lack of jointing or other structural discontinuities in the resistant units of these formations, as well as their good lateral stratigraphic continuity, may partially explain the relatively slow rate of headcutting in the spillway channel.

36. Spillway overflows and erosion. Considerable erosion of the spillway discharge channel occurred during a flood in July 1932 when the spillway was in construction and the reservoir was undergoing impoundment. Although this event was not large (13,000 cfs at the Brownwood Gage), it reportedly caused the most damage to the channel. As is well illustrated in the channel-bed surveys shown in Figure 20, successive overflows preferentially eroded the shales and caused headward migration of several knickpoints until, by 1976, a dramatic two-step falls occupied the channel between sta 3+00 and sta 4+50.

37. The Brownwood Gage measured floods of 19,800 and 26,500 cfs in May of 1941 and 1956, respectively. Unfortunately, detailed records of the spillway flow are not available.

38. Remedial and preventive measures. The CE formulated a series of recommendations regarding the repair of the spillway channel should the operating authorities choose to fund modifications to the project. These measures include the following:

a. Excavate and reshape the eroded area.

b. Protect vertical surfaces of exposed shale beds with shotcrete and wire mesh.

c. Use drainage material or pipe drains through shotcrete, where required.

d. Leave existing boulders on ledges in the discharge channel.

39. None of the above measures have been implemented to date. However, the Lake Brownwood spillway is expected to withstand several future overflows before facility safety becomes a concern. The spillway channel is regarded as

representing a good source of data on rates of erosion in vertically heterogeneous rocks.

Grapevine spillway

40. Background information. The Grapevine Reservoir spillway (on Denton Creek near Dallas, Texas (SWF)) flowed for the second time in its history during 21 days of 1981. Although the flow reached only about 5 percent of the design discharge, it produced severe, rapid, headward erosion in the channel, and a rugged erosional landscape was formed downstream with up to 30 ft of local relief (Figure 23).

Figure 23. Spillway discharge channel erosion at Grapevine Dam (Texas) during overflow of the emergency spillway in October and November 1981. The peak flow of 9,100 cfs was less than 5 percent of the spillway design flood

41. Grapevine Dam is located on Denton Creek in Terrant and Denton counties, 11.7 miles above its confluence with the Elm Fork of the Trinity River and approximately 20 miles northwest of the city of Dallas (Figure 2, No. 15). The dam was authorized by the River and Harbor Act of 1 March 1945. Construction of the project began in January 1948 with its completion in 1952. The deliberate impoundment of water began in July 1952.

42. The main embankment of the dam consists of compacted earth fill, is 12,850 ft in length, has a crest width of 28 ft at el 588, and is 137 ft above

the original streambed. The dam has a 13-ft-diam cut-and-cover conduit outlet controlled by two 6-1/5- by 13-ft electrically operated sluice gates. The Grapevine spillway is an uncontrolled off-channel chute-type concrete spillway 500 ft in length with the crest at el 560. Figures 24 and 25 show major features of the main embankment and spillway and the spillway plan and borehole locations prior to the recent construction of a shallow basin on the downstream toe of the apron. Other pertinent data concerning the engineering design data for Grapevine Dam and spillway are reported in US Army Engineer District, Fort Worth (1983).

43. Geology. Bedrock at both Grapevine and nearby Lewisville consists of strata of Upper Cretaceous Age striking roughly north-south and dipping to the east at low angles (Figure 26). At Grapevine, the bedrock consists of gently dipping, alternating beds of variable thickness and continuity, comprising soft-to-moderately hard, fine-grained, weakly to moderately cemented sandstone, soft sandy carbonaceous shale, and occasional thin (1 in. to 1 ft) seams of hard sandstone. The general stratographic aspects of this section are shown on the drilling cross sections (Figures 27-30). As can be seen from these sections, lithofacies changes are common and generally difficult to predict on a borehole-to-borehole basis, making correlation difficult (the borehole locations are shown in Figure 25).

44. The Woodbine strata in the Grapevine spillway area dip gently southeast at an average rate of about 2 percent (106 ft/mile). No major faulting or folding in general has been recognized in the Grapevine area and the subsurface investigation failed to detect any folding or faulting in the immediate spillway vicinity. Minor jointing and fracturing are present in the lithologes underlying the spillway discharge channel.

45. Weathering affects the strata to a depth of about 3 to 5 ft. Oxidation of the strata generally alters the shales to the consistency of stiff clay whereas sandstones tend to become indurated.

46. Overflow event, 1981. Flood overflows, peaking at 9,100 cfs (approximately 5 percent of the SDF (191,000 cfs)) during the period of 28 October to 21 November 1981, caused severe erosion of the spillway discharge channel from a point about 450 ft downstream from the Apron sill (sta 17+00, Figure 27) to areas nearly a mile downstream from the spillway along the discharge channel. The spillway channel flow destroyed two road crossings and deposited a large amount of silt on the Grapevine City Golf Course. The

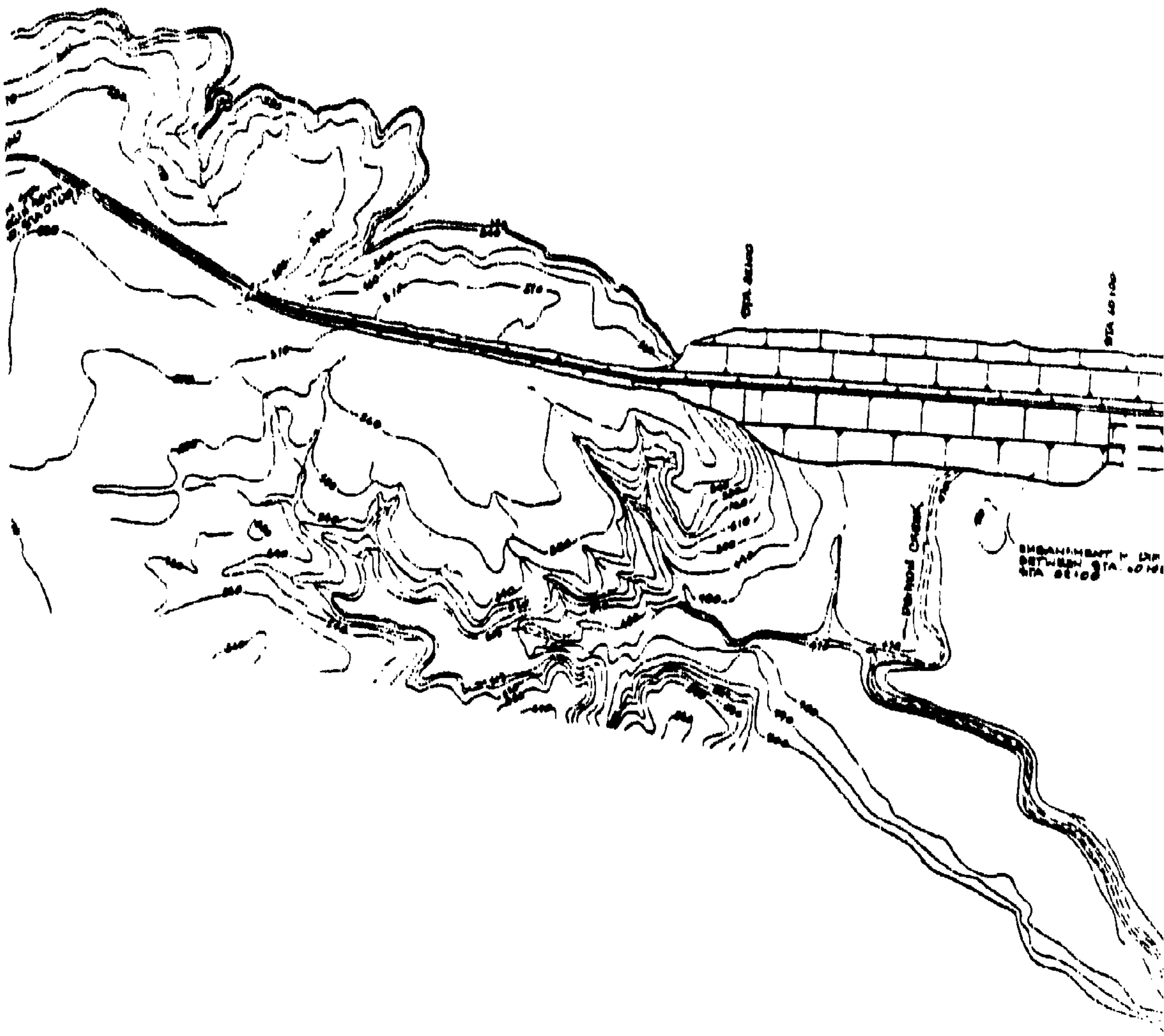


Figure 24. General plan,

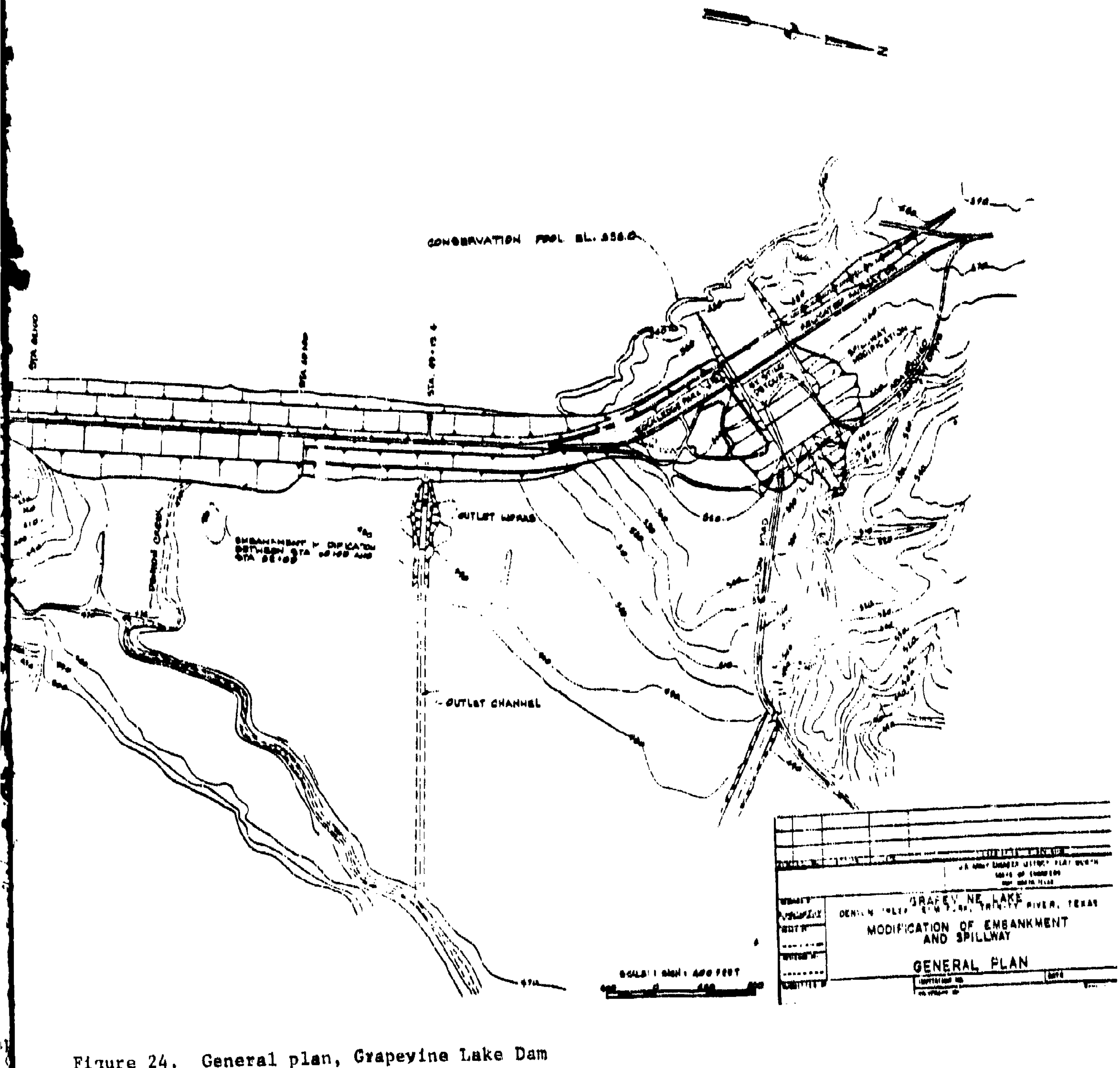


Figure 24. General plan, Grapevine Lake Dam

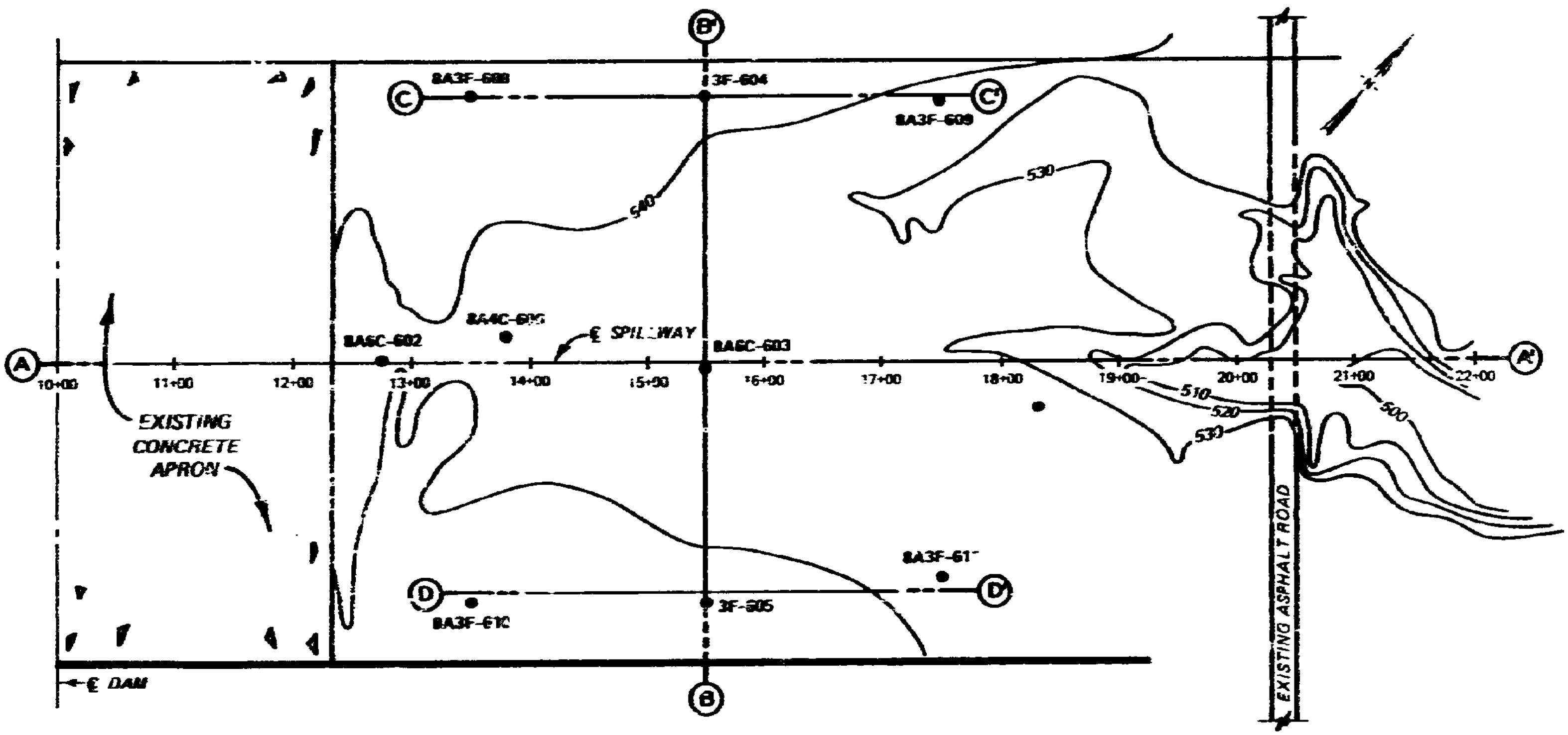


Figure 25. Grapevine emergency spillway discharge channel and borehole location plan

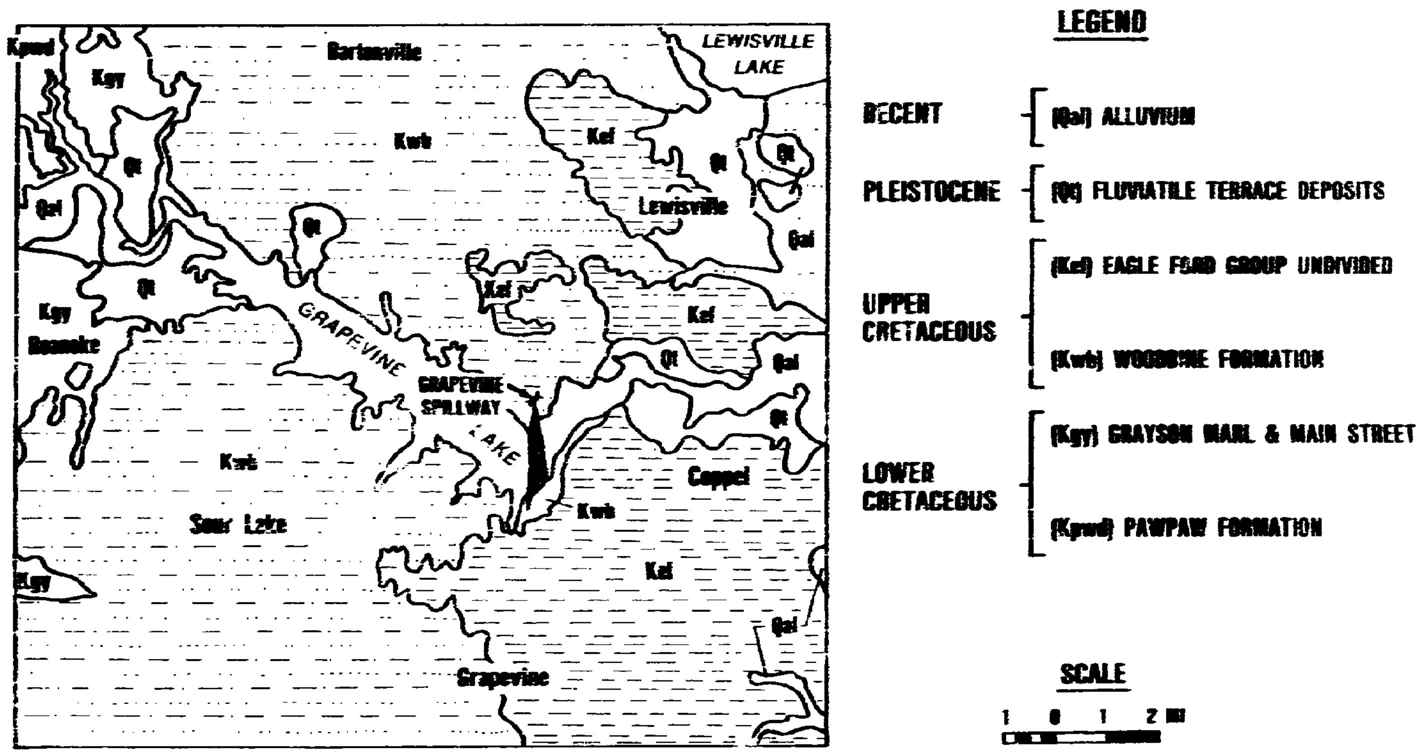


Figure 26. Geological map, Grapevine Lake and Lewisville Lake area

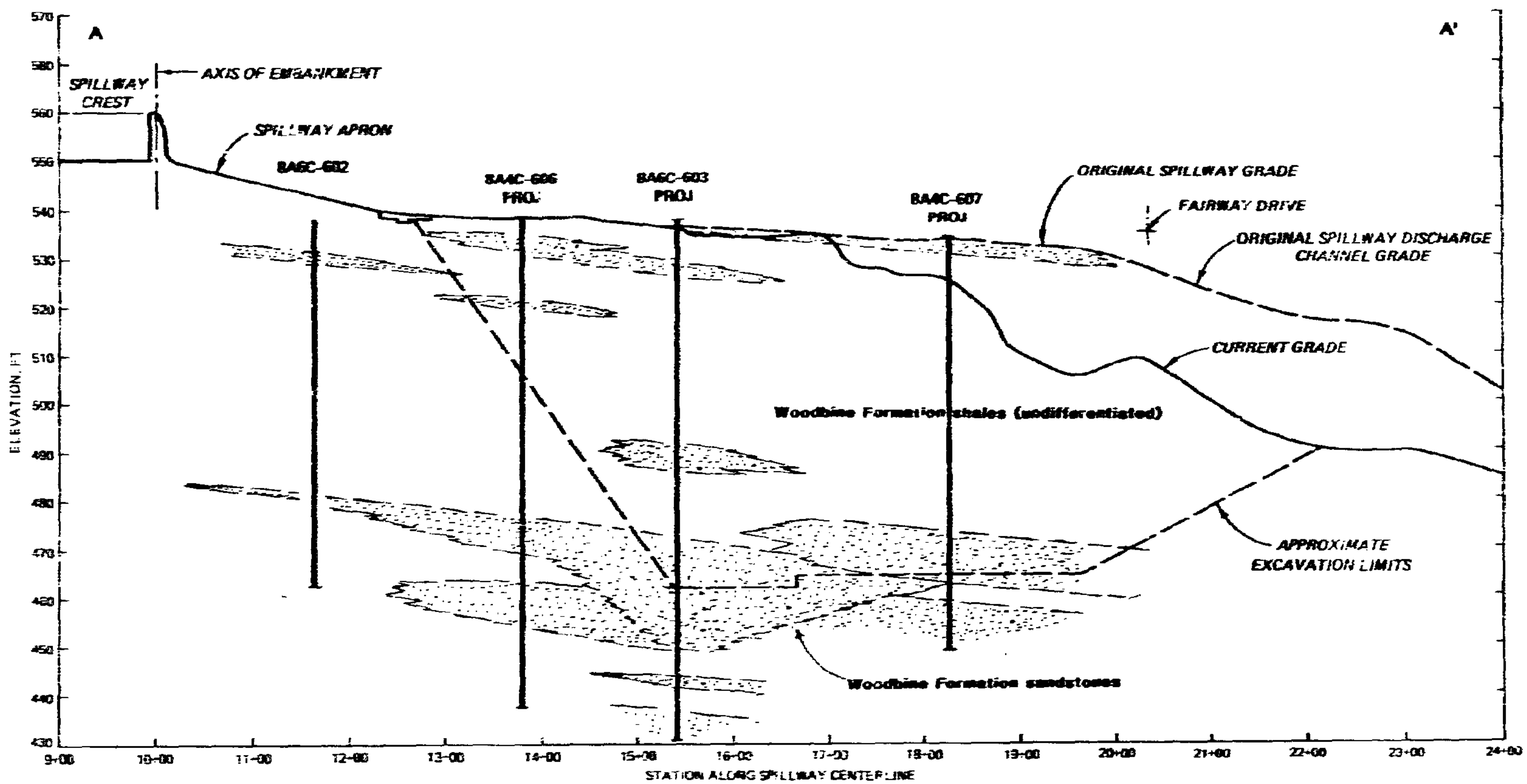


Figure 27. Geological profile along Grapevine emergency spillway discharge channel centerline showing the original channel grade as well as that formed by erosion during the 1981 overflow

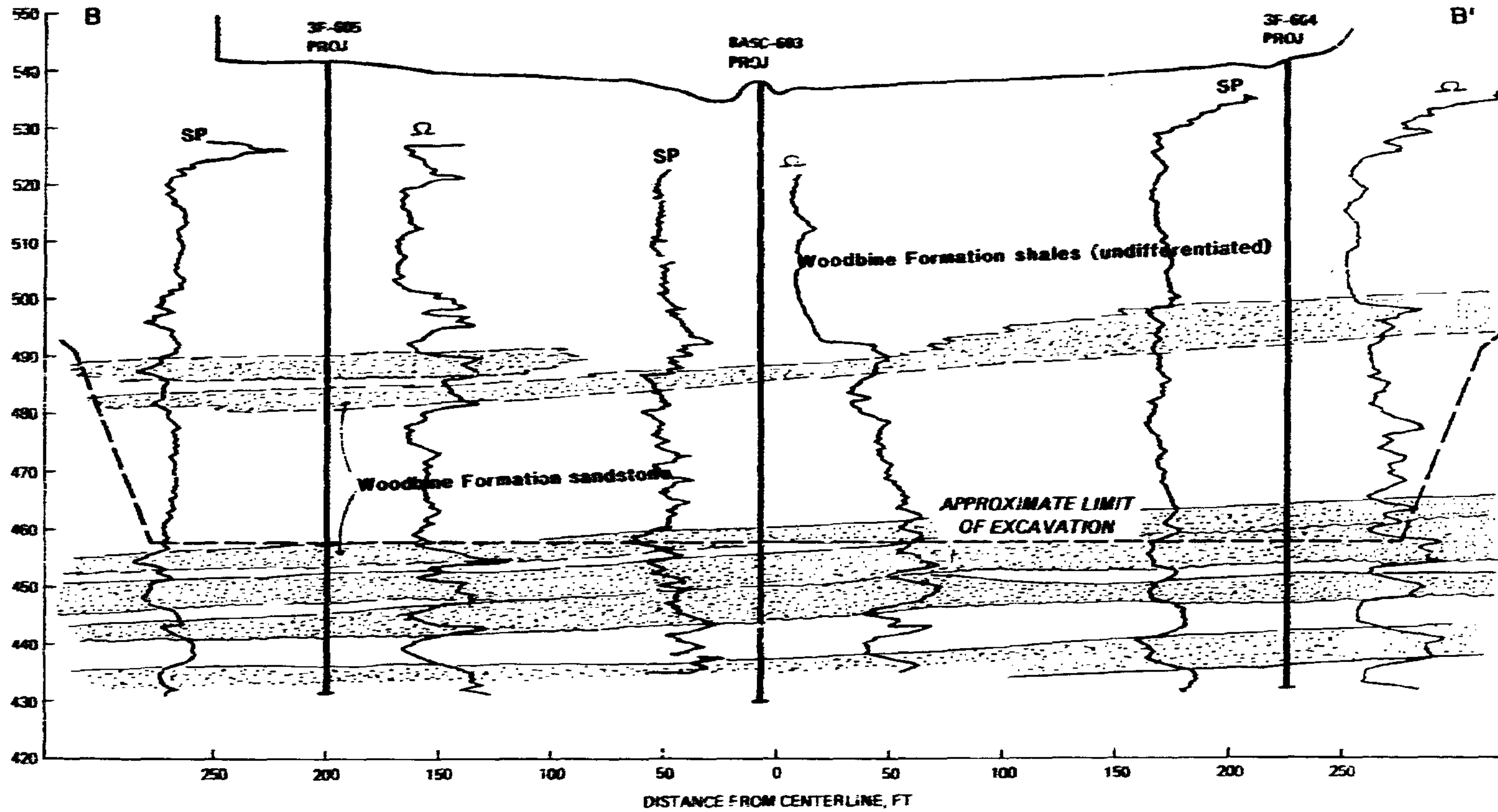


Figure 28. Geological cross section B - B' of the emergency spillway discharge channel at Grapevine Lake is based on borehole electric log interpretations and shows the infrared subsurface distribution of Woodbine Formation sandstones and shales

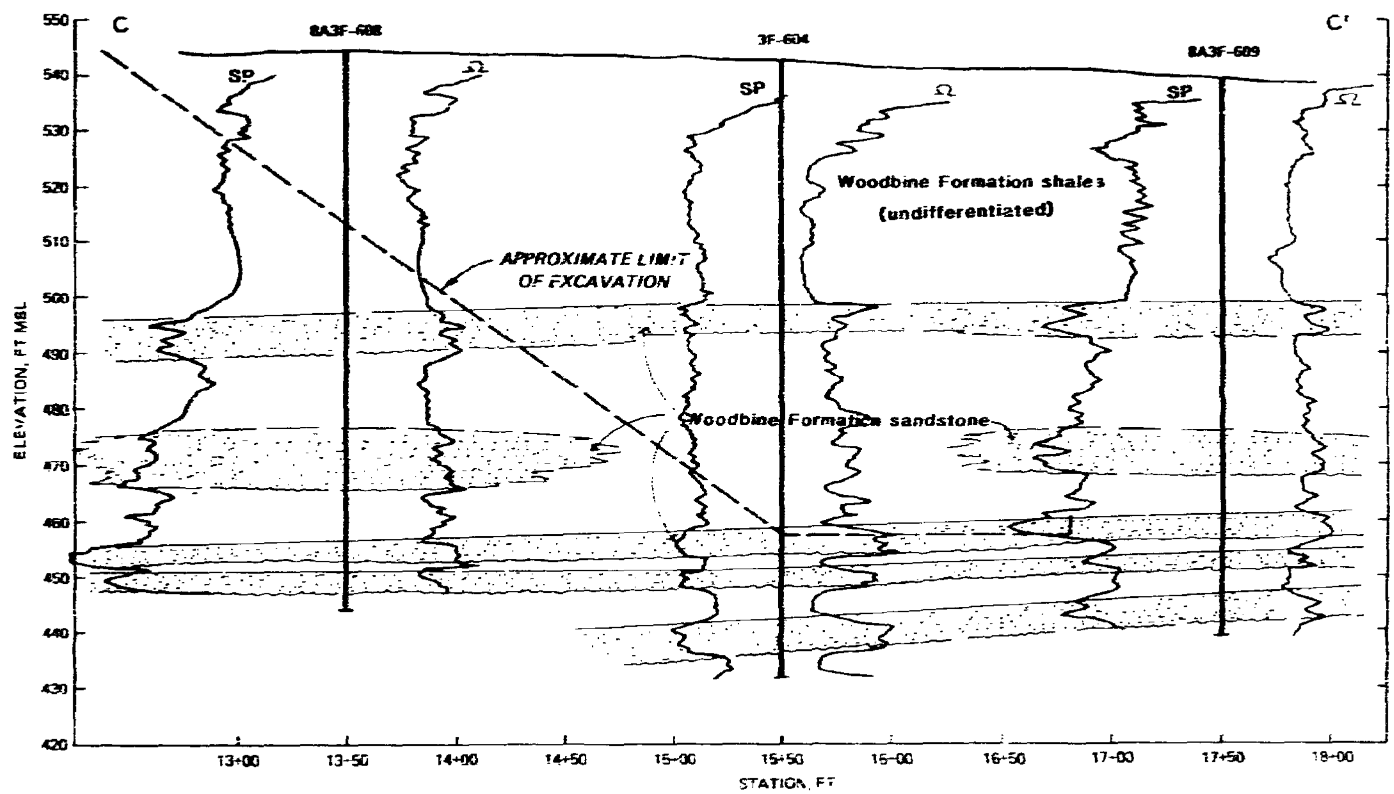


Figure 29. Geological cross section C - C' of the emergency spillway discharge channel at Grapevine Lake is based on borehole electric log interpretations and shows the infrared distribution of Woodbine Formation sandstones and shales

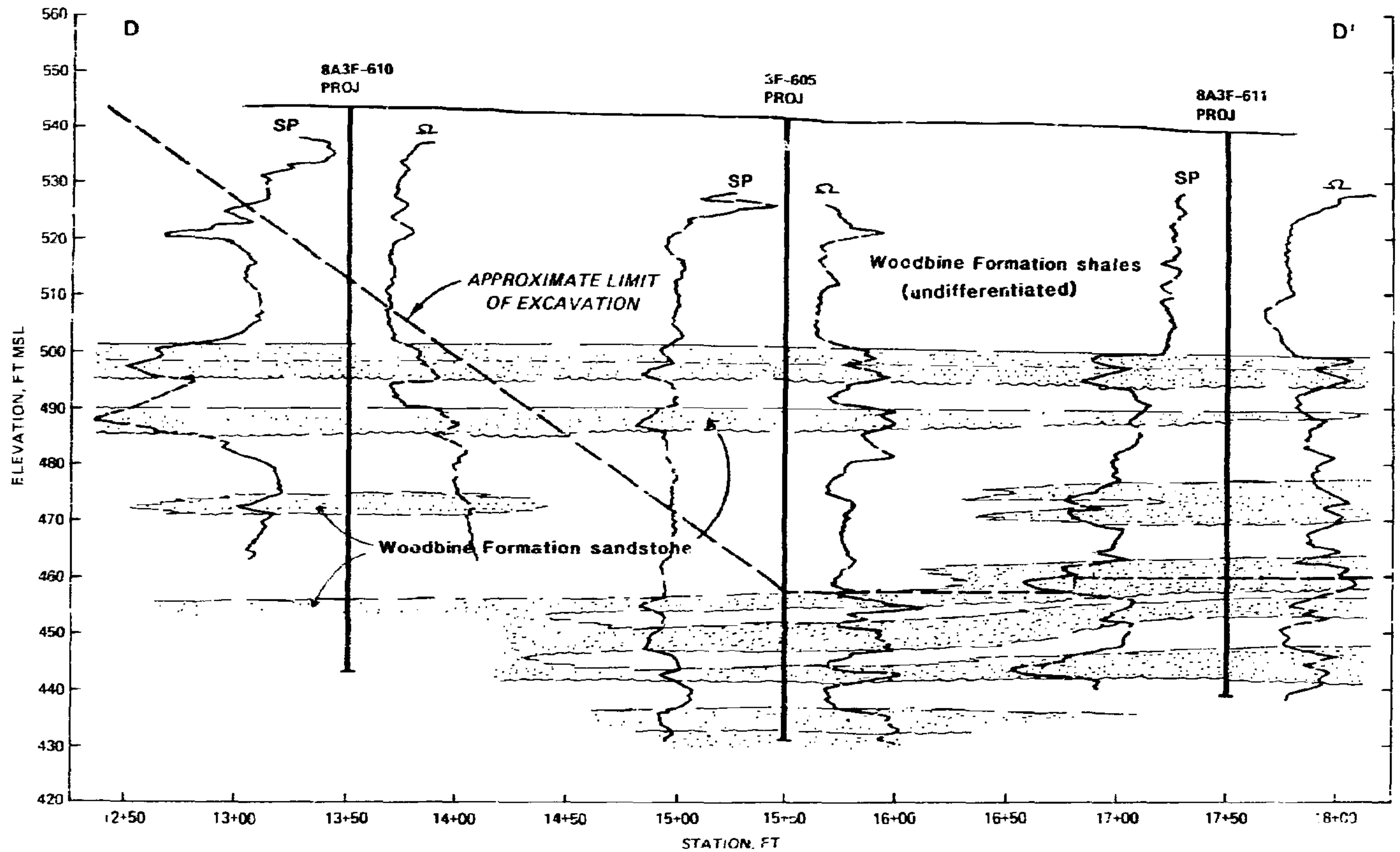


Figure 30. Geological cross section D - D' of the emergency spillway discharge channel at Grapevine Lake is based on borehole electric log interpretations and shows the infrared distribution of Woodbine Formation sandstones and shales

following excerpt from a District report by Alan Marr (SWF Geotechnical Branch) describes the causes of the erosion from a geotechnical point of view:

> The obvious factors which caused the severe erosion in the Grapevine Spillway during the November 1981 flood were the heavy discharge and the general erodibility of the Woodbine Formation materials. However, there were other factors which led to the severity of the erosion. These include the presence and location of the FM road embankment in the discharge channel, the high velocities of the discharge, and the inconsistancy of the Woodbine Formation materials.
>
> Gradational changes in the lithologic composition of the Woodbine Formation materials typically occur within short distances. The 5-foot thick layer of sandstone comprising the majority of the spillway floor did not extend to the area immediately downstream of the FM roadway embankment. Surface materials below the roadway embankment consisted of loosely compacted clayey sand overburden overlying weathered, soft, sandy shale. The road embankment, acting as a check-dam, caused a 3- to 4-foot head of water to accumulate. Once overtopping of the road embankment occurred, the increasing flow cut rapidly downward through the clayey sand and the underlying soft shale. The road embankment eventually collapsed and the deepening headward erosion began progressing at an accelerated rate. The sandstone layer at the surface of the unprotected discharge channel slowed the headward progression of erosion. However, once the sandstone layer was removed, the underlying sandy shale was readily removed by the churning flow which was then being concentrated into two deepening erosion channels. Discharge through the Grapevine Spillway eventually peaked at 9100 CFS flowing at a velocity of 35-40 feet per second.
>
> Later inspection in the erosion cut provided further evidence as to why the erosion was so severe. The shale exhibited several characteristics of erodibility such as softness, very sandy, poor compaction, and occasional jointing and cross-bedded structure. Occasional layers of moderately hard, fine-grained sandstone or siltstone separated the sandy shale strata. The sandstone layers, usually less than 1 foot in thickness, formed resistant ledges in the erosion slopes, contributing to the turbulence of the flow, and enhancing the undercutting of the softer shale strata.

47. Both the Grapevine and the nearby Lewisville spillways experienced similar flows during October and November 1981. The two projects are only 10 miles apart (Figure 26), and it may be assumed that meteorological conditions are the same at both projects (see below). However, the Grapevine

spillway discharge channel experienced severe erosion, whereas the Lewisville channel did not. The Lewisville channel is underlain by uniform, continuous, durable shales of the Eagle Ford Formation, and it is therefore tempting to ascribe the differences in response to spillway flow to this geotechnical factor alone. However, examination of the channel features suggests that hydraulic factors also played a major role. The channel at Grapevine was incised by a preflood brook and contained a sharp change of channel gradient just downstream from the preflood Fairway Drive road, whereas the discharge channel at Lewisville was flat, wide, and uniform with a gentle, unbroken downstream gradient. This major difference in channel hydraulics (and stability) between the two sites is discussed in detail in Part II of this report.

48. The District personnel estimated that the Grapevine spillway might fail if subjected to a flood greater than the 1981 100-year event. Such an event could cause catastrophic release of the reservoir and result in widespread flooding in the Dallas area downstream as well as severely limit the area's water supply. Remedial action involved the construction of a concrete chute and stilling basin on the downstream toe of the spillway. The spillway modification plan included the placement of excess excavation (from the stilling basin) on the floodplain section of the main embankment to help prevent skinslides and to relocate the Fairway Drive Road. The spillway modification was completed in October 1985 at a cost of $11 million.

Lewisville spillway

49. Background information. Spillway channel erosion at the nearby Lewisville Reservoir during the same flood event as that described above was much less severe than at Grapevine. The spillway design at Lewisville is similar to that at Grapevine, as were peak discharges (10,570 ft/sec on 18 and 19 October 1981 and 15,350 ft/sec on 2 November 1981), during the 1981 flood. The flood duration at Lewisville, from 15 October to 10 November 1981, was also very similar. Factors contributing to the pronounced difference in discharge channel response to spillway overflow include the excellent lithologic continuity and cohesiveness of the Eagle Ford Shale Unit underlying the channel (Figure 31) and the hydraulic stability of the channel which is wide and uniform with a gentle uninterrupted grade. The grass and soil lining the channel were peeled during the flow, and some minor erosion of shale occurred at the toe of the apron. This minor damage will be corrected by construction

Figure 31. Cohesive clay-shale in floor of Lewisville (Texas) spillway channel, scoured by 1981 overflow

of a concrete slab downstream to inhibit undercutting of the apron during future spillway overflows.

Sam Rayburn spillway*

50. Background information. Sam Rayburn Dam is located in east Texas at river mile 25.2 on the Angelina River, a tributary stream of the Neches River (Figure 32). This dam impounds the largest CE reservoir wholly within the state of Texas with 2,898,200 acre-ft of water covering a surface area of 114,500 acres at full power pool and is a multiuse project providing flood control, hydroelectric power, water conservation, and a major recreation resource in east Texas. The project is located in the "Big Thicket" country of east Texas in an area characterized by rolling and hilly topography and pine forests. The gentle slope of the land is south toward the Gulf of Mexico with a maximum relief of about 200 ft.

51. The Sam Rayburn spillway has never experienced overflow. The project is included here because it provides an excellent illustration of the circumstances leading to reevaluation of an unlined emergency spillway channel and raises doubts with respect to facility safety. The combination of revised

* PL 123/88/1, approved 11 September 1963, changed the name of this project from McGee Bend to Sam Rayburn Dam and Reservoir.

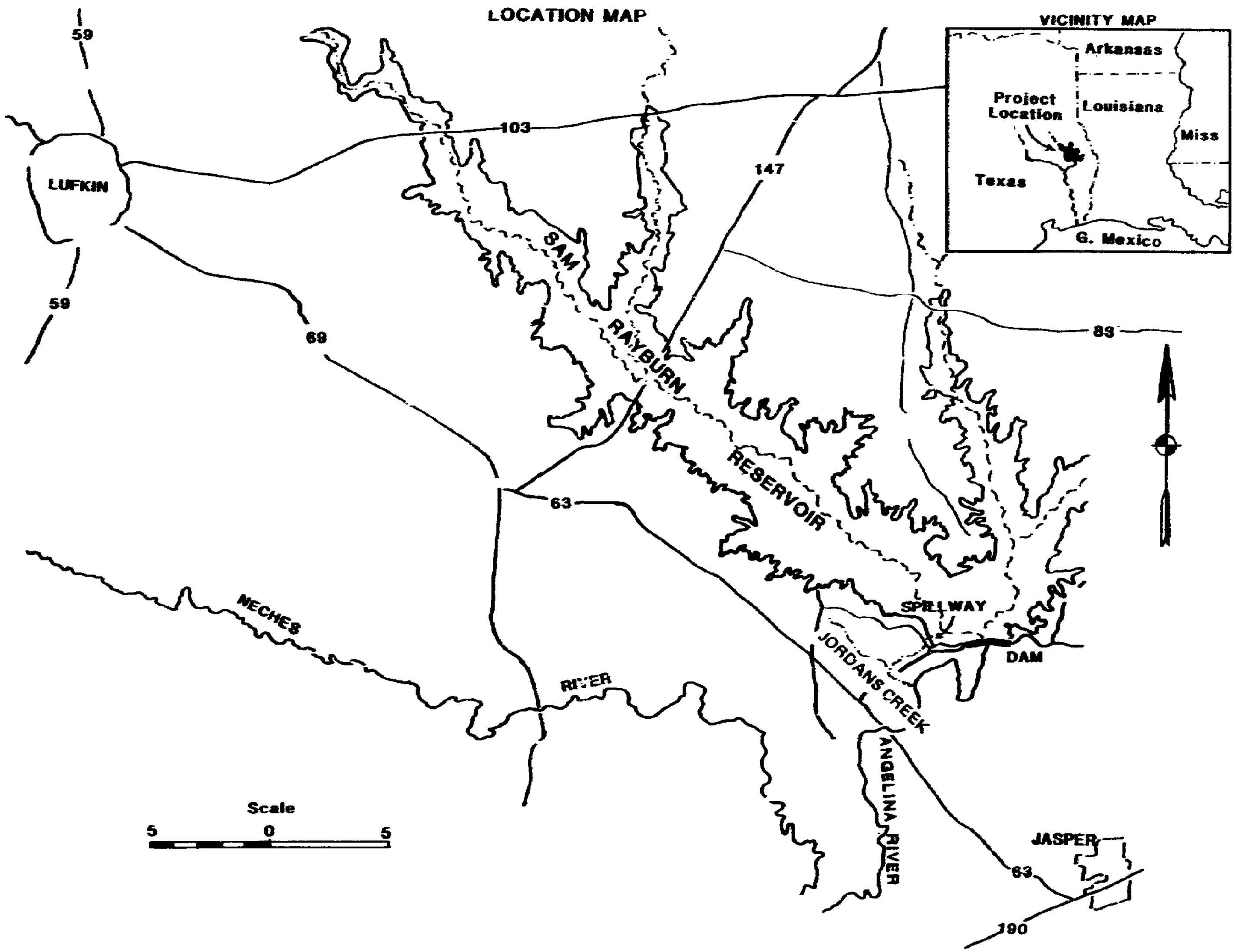


Figure 32. Sam Rayburn emergency spillway, location and vicinity map

hydrological criteria, which drastically increased PMF and SDF, coupled with an unlined emergency spillway discharge channel sited in relatively soft, non-resistant, easily erodible sediments resulted in considerable concern regarding continued safe operation of this facility. Reasons for this concern are discussed in detail in US Army Engineer District, Fort Worth (1984). This report considers a series of alternative remedial and preventive measures and recommends specific repair and rehabilitation works. These measures are currently being evaluated by the Fort Worth District.

52. Project construction commenced in September 1956 with deliberate impoundment starting in March 1965. The project includes a main earthen embankment, two dikes, an uncontrolled broad-crested weir spillway, and a combination hydroelectric powerhouse (52,000 kw) and gated outlet works. The rolled earth-filled embankment is approximately 12,400 ft in length with a crest width of 42 ft, a crest el of 190 NGVD, a maximum height of 120 ft, and a volume of 6 million cu yd.

53. The uncontrolled emergency spillway is located in a saddle about 7,000 ft west of the right abutment of the main embankment and about 5,000 ft west of the outlet works and powerhouse (Figure 32). The spillway is 2,200 feet wide at the crest el of 176.0. The control sill is an inverted concrete U-frame with a 15-ft-long by 2-ft-thick concrete slab (Figure 33). Inverted T-section cutoff walls extend into the 1V on 2H sideslopes bordering the spillway floor. Figure 34 shows the general plan, dike sections, and profile of the spillway as well as locations of auger and core boreholes used to evaluate subsurface conditions in the unlined discharge channel.

54. The unlined spillway discharge channel floor is formed by natural ground made relatively flat by alternately cutting and placing fill in separate areas of the spillway during construction. Below the concrete weir, the channel slopes downstream from el 175.5 to el 174.4 in 50 ft, then to el 172.0 in 133 ft and continues at this elevation for about 1,200 ft prior to entering a wooded draw which intersects Jordans Creek at nearly a right angle approximately 2 miles from the weir (Figure 32). Jordans Creek in turn empties into the Angelina River about 7 miles downstream from the dam.

55. Geology. The Sam Rayburn Dam and Reservoir is crossed by east-west trending sedimentary strata belonging to (in ascending order) the Claiborne and Jackson Groups of Eocene Age and the Catahoula Formation of Oligocene Age. The regional dip is gentle to the southeast in the area of the dam. In stream

Figure 33. View toward southeast along
2,200-ft-long broad-crested spillway
weir at Sam Rayburn project, east Texas

valleys, the Tertiary strata is covered by Quaternary Age alluvial deposits. Major structural features are absent in the reservoir area with the exception of some minor folding resulting from the continual loading of sediments to the south and from bed compaction.

56. The emergency spillway was constructed on clays, sands, and sandstones of the Catahoula Formation. The local well-drilling data indicate that the contact between the Catahoula Formation and the underlying strata of the Jackson Group occurs at an approximate el of -250, (±420 ft below the surface of the spillway discharge channel).

57. The Catahoula strata were deposited by coalescing streams as channel sands and overbank floodplain clays and silts. This resulted in a highly heterogeneous formation characterized by sudden facies changes and pronounced litho-stratigraphic discontinuity. This important aspect of the Catahoula

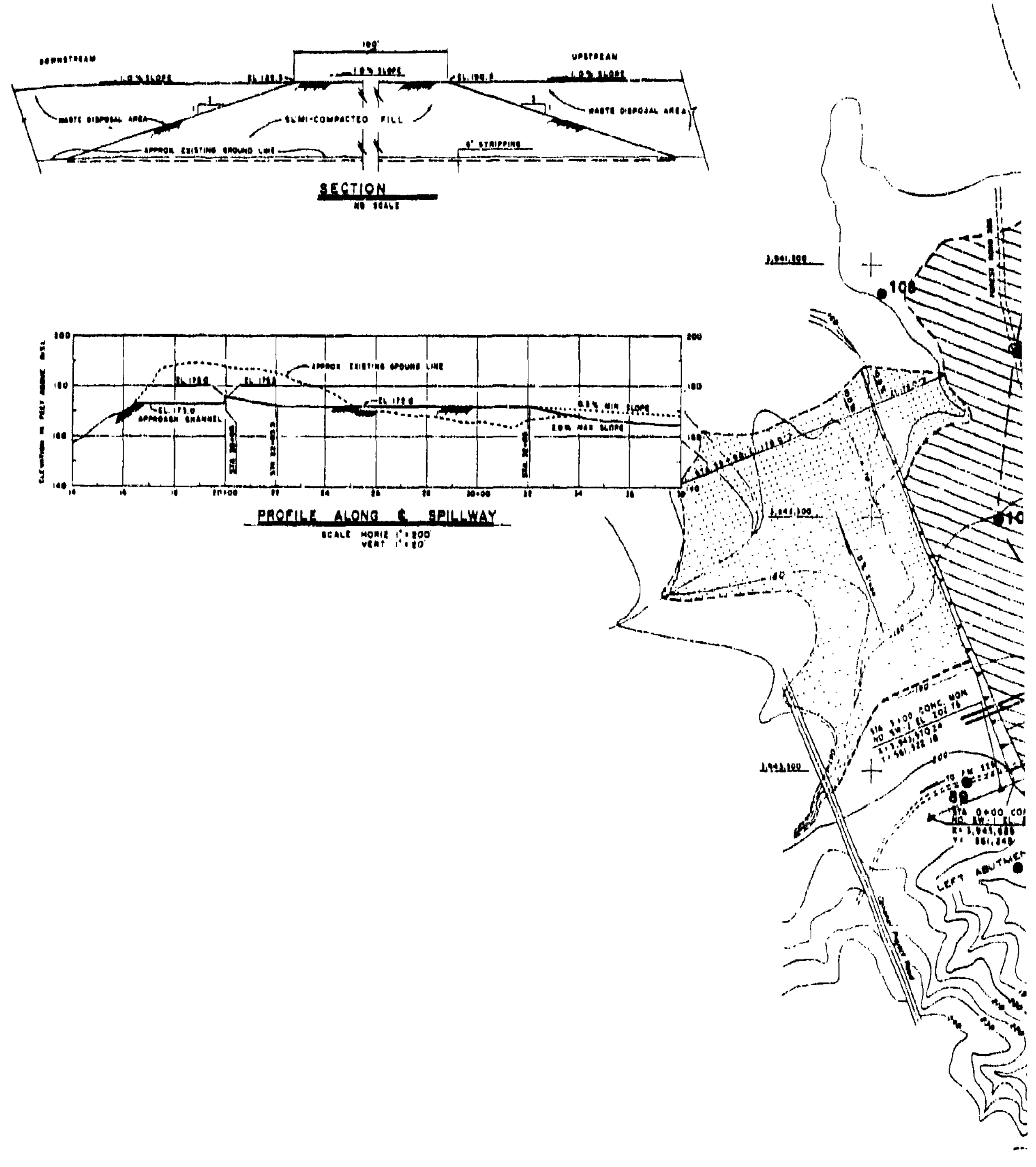
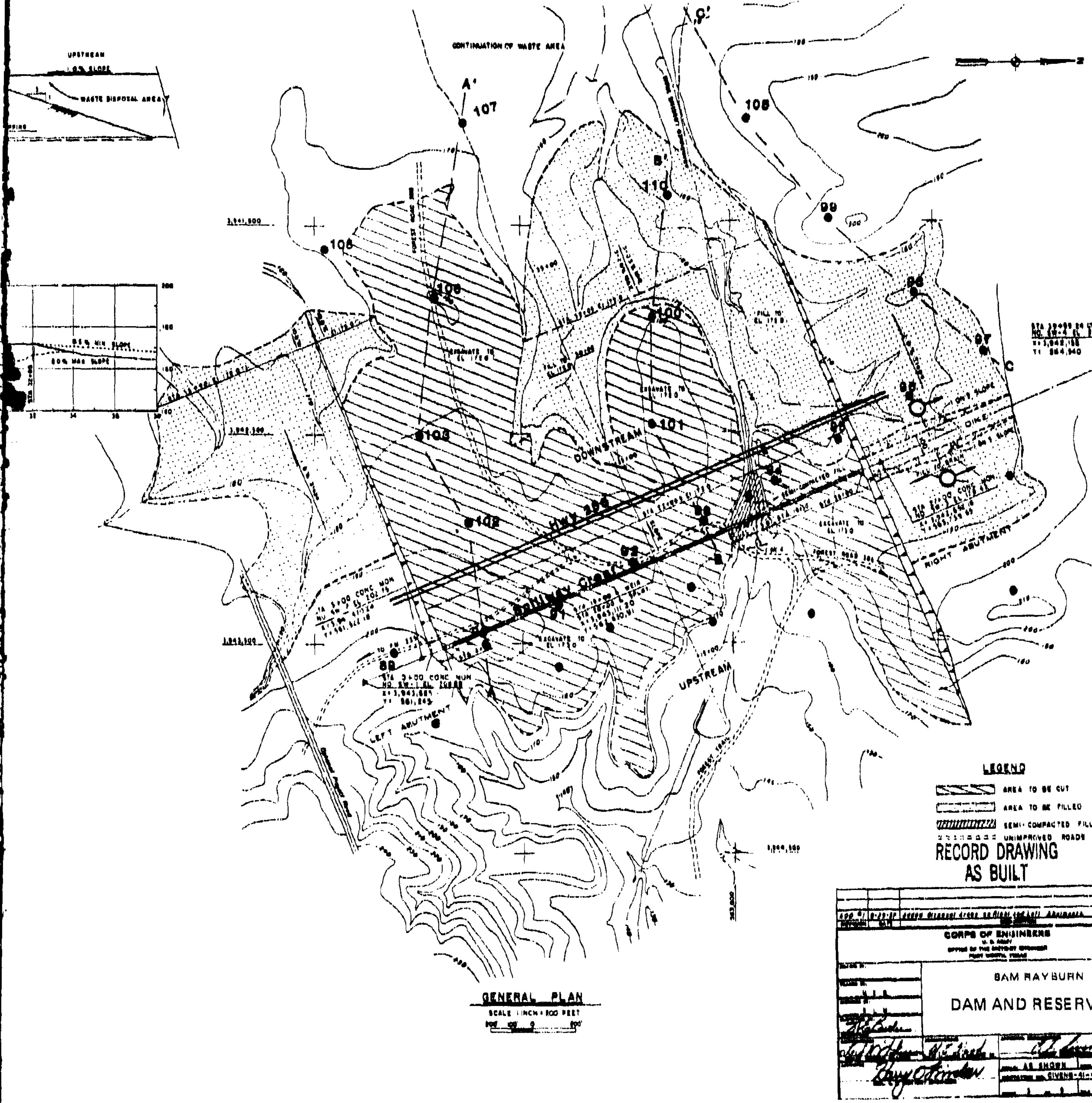


Figure 34. General plan, dike sections, and profil



34. General plan, dike sections, and profile, Sam Rayburn Dam emergency spillway

strata is illustrated by the interpretive drilling cross sections shown in Figure 35.

58. The Catahoula strata (flooring and underlying the discharge channel) consist of soft-to-moderately hard shaly clay; fine- to medium-grained loose sand; and hard, well-cemented, fine-grained, indurated sandstone. Clays (either tan or gray in color) vary from soft to stiff and low-to-high plasticity and are sandy and moist. Shales and clay shales are soft, massive, arenaceous, and often fractured with iron-stained surfaces. Bentonite and bentonitic zones, probably the product of devitrified volcanic ash, occur in some shale intervals.

59. The Catahoula sands and sandstones are described as fine to coarse grained, clayey or silty, and varying widely with respect to degree of cementation and induration. Frequently fractured, the fracture surfaces show prominent iron-staining. The sand-body thickness in the area underlain by the spillway channel varies from 1.0 ft (Boring 8A6C-250) to 29.0 ft, (Boring 8A6C-502).

60. A very important geochemical aspect of Catahoula sands and sandstones is that they change rapidly (with respect to degree of cementation and induration) according to proximity to surface exposure. This variable cementation can occur within the same sand body because of opaline silica, derived from the alteration of a contained volcanic component, which precipitates in surface and near-surface environments as opal-cristobalite, forming well-indurated, case-hardened sandstone. In the shallow subsurface, silica often remains in solution (a function of lower temperature). Thus, a well-cemented, indurated, hard sandstone at the surface often gives way to loose uncemented sand in the shallow subsurface.

61. This pattern of variable cementation means that should scour during spillway overflow remove the resistant surface exposure of a Catahoula sand body, the rate of erosion might increase dramatically if the flow encounters loose, nonresistant, subcropping sands of the same unit.

62. The regional dip of the Catahoula Formation in the spillway discharge channel is gentle toward the southeast at a rate of 120 ft/mile. No major faults have been noted although minor joints and iron-stained fractures were noted both on the surface and in cores.

63. Recent District geotechnical investigations of the spillway revealed that no significant erosion-resistant strata which occur near the

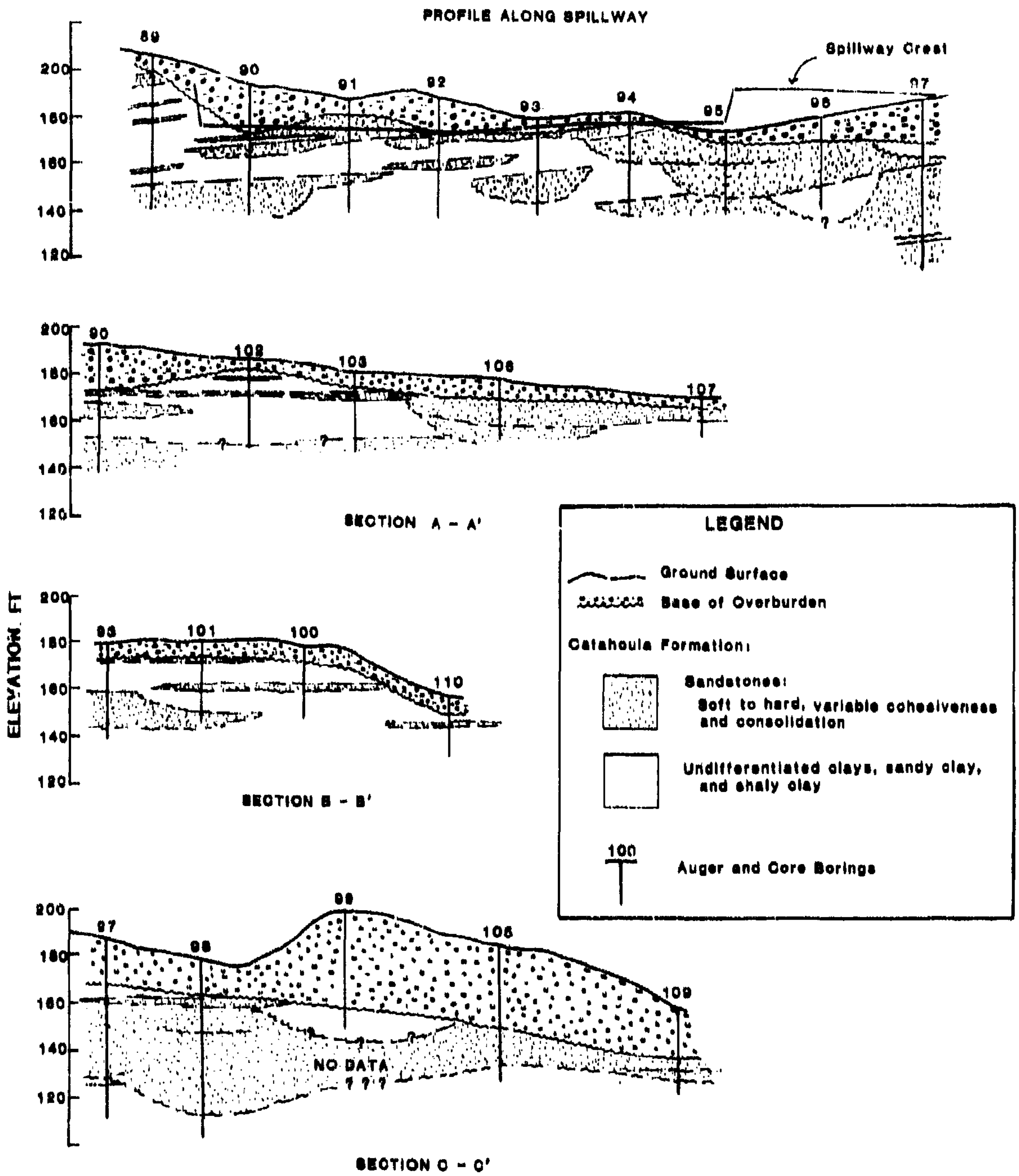


Figure 35. Interpretive geological cross sections, Sam Rayburn emergency spillway discharge channel

surface of the spillway are continuous across the entire spillway discharge channel area. The rocks underlying the spillway channel, especially when compared with the material recently eroded from the Grapevine Lake spillway, are classified as being highly erodible.

64. Hydrology, hydraulic design, and erosion potential. The US Army Engineer District, Fort Worth (1984) addresses two specific deficiencies found at the Sam Rayburn project--inadequate embankment freeboard, and erosion potential of the uncontrolled spillway floor and discharge channel.

65. Use of new hydrological criteria (related to design and safety) developed a PMF that resulted in a maximum-design water surface of el 187.9. The criteria set forth in Engineer Technical Letter (ETL) 1110-2-221 require a design freeboard of 7.9 ft. Since the top of the dam is at el 190.0, the height of the main embankment is inadequate with respect to freeboard requirements by 5.8 ft.

66. The revised hydrology for the project has increased the depth of the PMF flow through the spillway from 7.1 ft to 11.9 ft and increased the flow duration to in excess of 28 days.

67. District hydraulic studies, which computed velocities and tractive forces at various locations in the spillway channel for different depths of flow, concluded that a potential exists for extensive erosion at minimal discharges. The passage of flows approaching the PMF spillway flow could possibly cause failure of the spillway through excessive erosion, leading to catastrophic release of the reservoir waters.

68. Failure of the Sam Rayburn spillway and catastrophic release of the reservoir waters under the conditions outlined above would probably occur when the surrounding region is saturated by recurring rainstorms and severe flooding is occurring on a swollen Neches River system. A release of the Rayburn Reservoir waters could also result in damage or loss of the B. A. Steinhagen Dam (Dam "B"), which is located approximately 12 miles downstream and serves as a resettling reservoir for the Rayburn hydroelectric dam outflow.

69. Remedial and preventive measures. The US Army Engineer District, Fort Worth (1984) documents the downstream damages, loss of life, and forfeiture of substantial revenues should the failure of the Rayburn spillway transpire. The cost of consequent litigation is not discussed but should also be factored into any realistic scenario of a disaster of this magnitude. The report discusses a series of alternative remedial measures involving repair

and rehabilitation of both the main embankment and the spillway discharge channel. To remedy the problem of erodibility of the spillway discharge channel only, the following measures are being evaluated by the District:

a. Concrete paving on the spillway channel. This measure would minimize the erosion potential of the spillway but would require 18 in. of reinforced concrete paving to be laid on the first 2,000 ft of the channel. This alternative has an estimated cost of $85 million. Passage of the PMF spillway overflow could still result in failure of the spillway weir. Lesser flows might result in extensive damages to the channel.

b. Rollcrete paving on the spillway channel. This alternative requires 24 in. of reinforced rollcrete paving covering the first 2,000 ft of the discharge channel. Damages requiring extensive repairs may result from passage of significant spillway discharge, and the integrity of the spillway is not "guaranteed" should passage of the PMF spillway overflow occur. This alternative has an estimated cost of approximately $62 million.

c. Soil-cement stabilization of the spillway channel. Soil-cement stabilization of the first 2,000 ft of the discharge channel to a depth of 36 in. could also minimize the erosion potential of the channel. Like the first two alternatives, this measure does not guarantee the survival of the spillway during PMF overflow, and extensive repairs are anticipated after the passage of significant discharge. The soil cement stabilization of the channel could be completed for an estimated cost of $26 million.

d. Drilled pier cascade system. The construction of a deep drilled pier cutoff wall along the alignment of the existing spillway weir and a series of three additional cascade walls across the spillway discharge channel could prevent total failure of the spillway. Extensive repairs would be required after the passage of any significant spillway discharge. This system has an estimated cost of $50 million.

70. A further alternative proposed by the District involves the construction of a new ogee weir, crest el 143.0, controlled by eight 40- by 33-ft tainter gates in the main embankment at the former closure section. The spillway weir would be blocked to el 190.0. This alternative, the best from a hydraulic design consideration, would satisfy freeboard requirements and would control erosion from spillway releases (which would be routed to the main channel of the Angelina) at a minimum cost. This alternative could be constructed for an estimated cost of approximately $58 million.

71. Due to the probability that passage of a PMF could cause total failure of the spillway and catastrophic release of the reservoir, a "do nothing" alternative was not favorably considered. Because of the potential

for loss of life, $146 million in potential property losses, and $43 million of lost annual benefits that would result from a failure, the District has recommended that the deficient conditions at Sam Rayburn be rectified to ensure the safety of the project.

DMAD spillway

72. The DMAD Dam is a privately owned and operated project located on the Sevier River in west-central Utah, northeast of the town of Delta (Figure 2). Engineering, hydraulic, and geotechnical data for this project are not available at this time. However, the REMR work unit observational data base includes a videotape and a collection of photos that dramatically document the spillway failure and the catastrophic release of the 16,000-acre-ft reservoir during the initial spillway overflow in July 1983. Follow-up work to determine the preflood geotechnical and hydraulic conditions in the spillway channel is planned for FY86.

73. The floods during July 1983 affected large areas of Utah. Extensive flooding along the Sevier River caused the DMAD emergency spillway to operate for an extended period of time. Spillway flow washed out an old diversionary structure in the downstream discharge channel and created a 15- to 20-ft-high waterfall. Excessive scour resulted in rapid headward migration of this knickpoint (approximately 0.5 mile in 24 hr). For reasons as yet unknown, the knickpoint stabilized for 2 days at a point several hundred yards downstream from the spillway structure.

74. Shortly thereafter renewed scour caused the knickpoint to move rapidly headward--this time at a rate approximating 1 ft/min. Despite efforts to impede scour by the use of hastily placed riprap and concrete-filled automobiles, the spillway structure was undermined and failed (Figure 36).

75. The failure of the spillway structure and the sudden release of the 15,000 acre-ft DMAD Reservoir resulted in a downstream "domino" effect. The Gunnison Bend Dam was breached to provide a controlled release of its 7,000 acre-ft of water before the arrival of the DMAD waters caused overtopping of its embankments. This release, combined with the DMAD waters, caused widespread flooding in and around the town of Deseret with considerable property and agricultural damage.

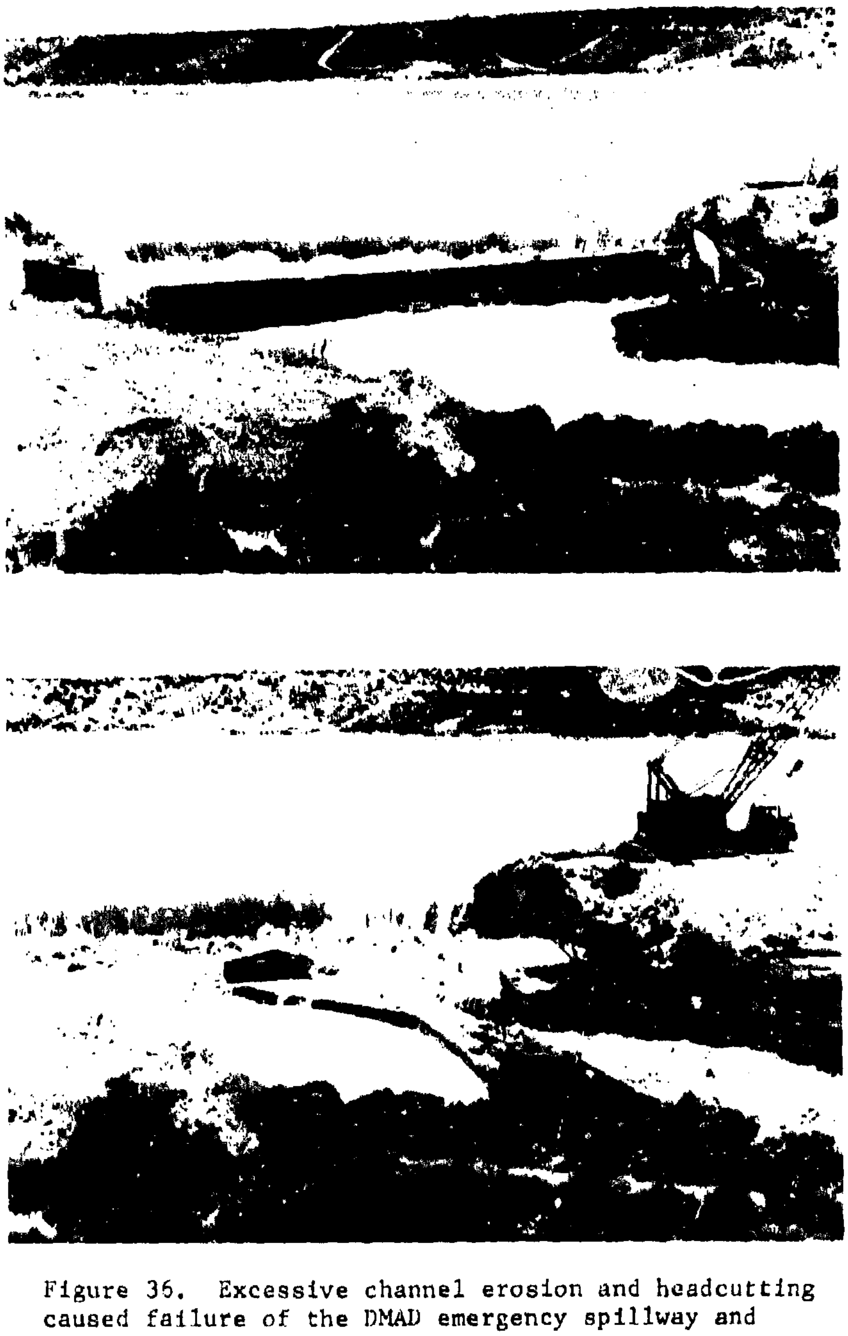


Figure 36. Excessive channel erosion and headcutting caused failure of the DMAD emergency spillway and catastrophic release of the reservoir waters

Data Base Management

76. The success of REMR efforts in the rock erosion in emergency spillway channels problem area depends on the compilation of an accurate and comprehensive data base which can be used to (a) develop methods and techniques to predict accurately the cause and extent of erosion during spillway flow in site-specific cases, (b) guide the selection of appropriate preventive or remedial measures, (c) predict the nature and extent of impacts on the downstream channels and infrastructure, and (d) implement timely technology transfer to interested personnel in CE Districts and other Federal, state, and local interests. Figure 37 illustrates the central role of the work unit data base.

77. The randomness of emergency spillway overflow and the diversity of the soil and rock subjected to sudden hydraulic scouring forces during this flow dictate that the data base contain both empirical (observational) elements and experimental data. Continual rigorous attention to the adequacy and accuracy of the geological, hydrological, hydraulic, and engineering design components of the data base forms an essential part of the program.

78. Information input to the data base generally takes the form of (a) CE Periodic Inspection Reports, (b) information derived from literature studies, (c) written reports of site visits, (d) accompanying 35-mm slides and photos, and (e) videotapes of spillway overflow events. Whereas the first four provide essential background information for detailed case histories (which include preflood, flood event, and postflood analyses), the fifth invariably provides the most dramatic documentation of the overflow event itself and its impact on the spillway structure and channel.

79. The strategy employed in acquiring the background information used in this report is summarized in Appendix A, and brief summaries of 25 site visits are presented in Appendix B. This inventory is not complete and site visits to projects in several Districts are planned for FY86 (e.g. the Cochiti and Jemez Reservoirs in Alburquerque District, the DMAD damsite in Utah, and the Johnny's Creek area near Fort Payne, Alabama (SAM)).

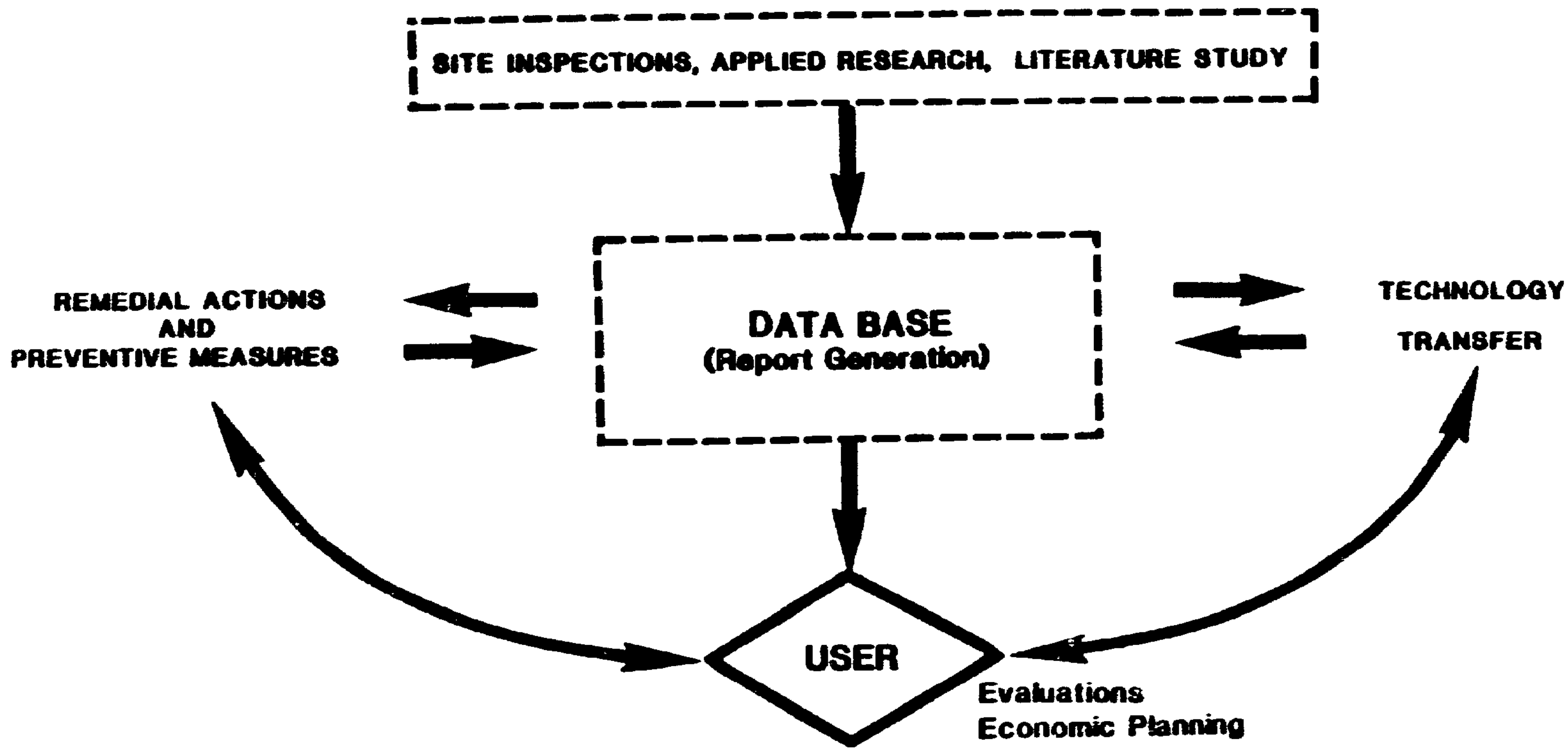


Figure 37. Rock erosion in emergency spillway channels work unit format

PART II: FACTORS CONTROLLING EROSION AND OTHER RESPONSES TO EMERGENCY SPILLWAY FLOW

80. The response to spillway flow is ultimately controlled by a variety of hydraulic and geological factors. Because the physiography, hydrology, fluvial geomorphology, and geology vary from basin to basin (and within many basins), these factors must be evaluated on a site-specific basis. Major factors identified by this study include the effects of channel gradient changes and geologic discontinuities in rock and soil. In fact, because all these factors are (to varying degrees) interrelated, a discussion of one factor may be repeated in connection with another.

Hydraulic Factors

81. The following hydraulic factors exert major controls on channel response to spillway flow:

- a. Flood frequency, magnitude, and duration.
- b. Engineering design.
- c. Channel gradient(s).

Each of the above factors is discussed in the following paragraphs. The results of this study indicate that change(s) in channel gradient, often linked to geologic discontinuity, is a key factor in controlling downstream erosion in some settings--specifically in unlined channels floored with soft and poorly indurated sedimentary rocks. Any relatively sharp change in the gradient of an unlined spillway channel may be the result of lithoflacies (specific rock type) change or structural discontinuity. Detailed studies should determine the cause of channel gradient changes and their response to spillway flow. The engineering design of the spillway structure and spillway discharge channel is a matter of crucial importance in dam projects and therefore deserves singular attention in any evaluation of spillway channel erosion potential on a site-specific or site-comparison basis.

Flood frequency, magnitude, and duration

82. The estimation of flood frequency and magnitude results from complex and often difficult hydrologic studies dedicated to the understanding of basin precipitation (input) and runoff (output) relationships. These studies involve the measurement of intrabasin precipitation, evaporation,

infiltration, transpiration, percolation, and storage. Flood frequency and magnitude are estimated on the basis of measurements made over as long a period of time as is possible for a given basin.

83. In many areas, until recently, there were not enough stream-gaging stations with sufficient historical data or proximity to the problem area to provide direct determinations of desired streamflow (floods, average flow, low flow). In other areas, clear-cutting and intensified land use have affected both input and output relationships.

84. Several reasons can be cited for changes in flood frequency and magnitude estimations. Most cases involve an enhanced data base and the use of modern methods for predicting flood frequency and magnitude. These methods tend to be based on the concept that the drainage basin acts as an integrator, summing all of the inputs and yielding outputs which are the net result of all the hydrologic and geologic processes acting on those inputs (Osborne 1976). Changes in estimates of flood magnitude (and therefore the design flood for the dam and spillway) are of critical importance in assessing facility safety and performance. Flood frequency has an impact on the erosion potential of unlined emergency spillway channels. High-flow frequency can require that the engineering design of the spillway be enhanced, particularly with respect to energy dissipators and the construction of a stable downstream channel grade, often at considerable cost. The duration of floods which result in spillway overflow is often a fraction of drainage basin and reservoir size. As with high flood frequency, long duration of flooding and spillway overflows may require more elaborate design of the emergency spillway and its discharge channel.

Engineering design

85. The passage of floodwaters over an emergency spillway is an event of potentially great danger to very costly structures, to say nothing of the threat to human life and property, or disturbances to downstream ecological balance, navigation, and industry. Therefore, spillway structure and channel design are matters of crucial importance in dam projects.

86. Spillway design plays an important role in controlling the rate and intensity of downstream erosion in downstream discharge channels. The empirical data base and several important case histories (see Part I) indicate that discharge channels characterized by large-scale geologic discontinuities in sedimentary rocks of variable cohesiveness and gradient change(s) are unstable

and particularly prone to severe scour during spillway flow. In some cases the impact of erosion may be mitigated by the construction of energy dissipation structures at the downstream toe of the spillway, particularly if initial flow(s) and discharge channel erosion have served to stabilize the downstream channel. The stilling basin at the Grapevine Spillway was recently constructed (after the initial flow had severely eroded the discharge channel) to safeguard the spillway during future overflow events (Figure 38).

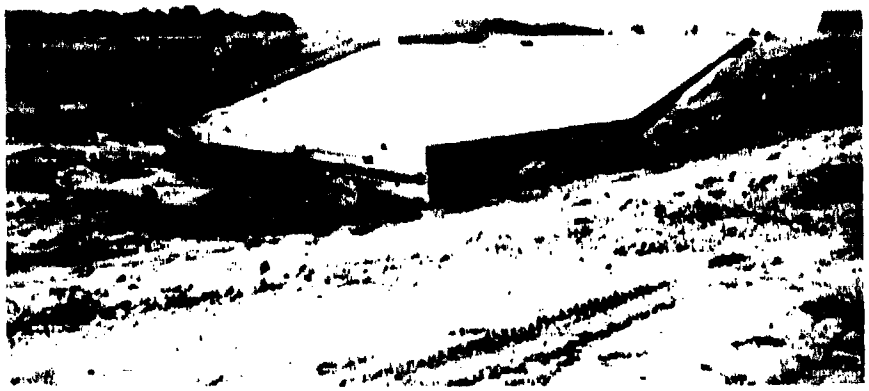


Figure 38. Remedial construction at Grapevine project. Energy will be dissipated in deep, large-volume plunge pool beneath extended concrete apron

87. The Sardis, Enid, and Grenada Dams in Mississippi (US Army Engineer District, Vicksburg (LMK)) have unlined spillways, all of which have experienced several flow events (up to 4,000 cfs) of long duration (up to 86 days). The channels are in shales and sandy clays of variable cohesiveness. Although a considerable amount of erosion has affected these channels in their downstream reaches, the structures were not threatened because large, properly positioned energy dissipators at these installations reduced the flow velocities and minimized the erosional impacts in the subcritical discharge-channel discharge of the spillway. Erosion of the unlined channel at Sardis is further mitigated by the excellent lithologic continuity of the shale unit forming the channel sides and bottom. Erosion that has occurred has moved a

considerable amount of material to the main channel where it has been removed by dredging.

88. It should be noted that energy dissipation structures at the head of unstable discharge channels (i.e. those sited in erodible materials with steep grades or sharp gradient change(s) or those not sited at elevations which will ensure adequate tailwater elevation) may serve no useful purpose since severe erosion will still occur in the downstream channel. For example, building energy dissipation structures at the head of preflood unstable discharge channels at Grapevine (SWF) and Saylorville (NCR) projects would have proved to be a useless exercise in terms of the channel erosion experienced in initial overflows. As a case in point, the lack of an energy dissipator at Lewisville spillway (SWF) did not endanger the spillway or its discharge channel. The discharge channel at Lewisville is wide and even with a gentle uniform gradient and is formed in continuous durable shale with a low structural dip. The erosion is minimal or at least manageable at low cost under such conditions without recourse to expensive energy dissipation measures.

89. In summary, many unlined channels constructed in sedimentary rocks of variable cohesiveness and continuity are often unstable because of associated channel gradient changes or incipient knickpoints. Such channels will respond adversely to the hydraulic force of a large-volume supercritical flow, especially if the channel is narrow, and spillway structures may be endangered by excessive headcutting scour during overflow events. Should spillway flow occur frequently in these channels, preventive or remedial measures to protect the channel are often necessary to safeguard spillway integrity.

90. The ramifications of a change in the PMF are well illustrated by the case of the Sam Rayburn project in east Texas (see Part I). A change in the PMF left that dam with inadequate freeboard to meet flood-control requirements and increased the depth of the PMF spillway flow by 68 percent--from 7.1 ft to 11.9 ft above the spillway crest. This change sparked an evaluation of the unlined spillway channel. The results indicate that all of the controlling factors are in place to cause failure of the channel by excessive scour should the spillway experience a significant flow. Because of the large area of the reservoir, the flow would be of long duration. The downstream impacts of such an event are unacceptable. The recent evaluation has led to District recommendations for remedial and preventive actions totaling in excess of $10 million.

Channel gradient

91. The impact of gradient change in an unlined spillway channel cannot be stressed too strongly. Intuitively one would expect the degree of erosion to be closely related to the hydraulic force and kinetic energy of the water acting on the rocks and/or their derived soils forming the channel. The energy transmitted to the channel is a function of velocity and depth of flow. The Manning Equation for steady, uniform open channel flow (below) shows that velocity varies with the square root of the channel gradient. Hence, changes in channel gradient can increase the amount of energy available for scouring (granted that the flow conditions in many spillway discharge channels are anything but steady or uniform).

$$\text{Manning Equation:} \quad V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

where

V = velocity, fps

n = channel roughness coefficient

R = hydraulic radius, ft

S = channel gradient

92. The Manning Equation also shows that the velocity varies inversely with the channel roughness coefficient, a measure of the resistance to flow in a channel. Several authors emphasize that this coefficient is very difficult, if not impossible, to select exactly. Furthermore, unlined spillway channels with complex geology (i.e., a large number of lateral and vertical large-scale discontinuities) can be expected to have roughness coefficients which vary markedly within the channel. From this it can be inferred that the interrelation of channel gradient change and geologic discontinuity can often result in changes of roughness coefficient along an unlined spillway channel. Interested readers are referred to Chow (1959) for a comprehensive discussion of the factors affecting Manning's roughness coefficient for open channel flow.

93. The effect of channel gradient change is well illustrated by empirical observations at Grapevine and Lewisville (SWF), both of which are described in Part I. Both of these projects experienced spillway overflows following a period of high rainfall in the fall of 1981. The two projects are only 10 miles apart, and it may be assumed that meteorological conditions were

approximately the same in both areas. Flow peaks and duration were also similar. Erosion impacts at Grapevine were substantial, whereas at Lewisville they were minor. It is believed that the differing channel gradients and gradient changes, differing channel widths, and considerable differences in lithologic continuity were responsible for the marked differences in erosional effects between the two facilities.

94. The Grapevine spillway is underlain by interbedded sandstones and shales of the Cretaceous Woodbine Formation. These lithologies are variably indurated and weathered and offer variable resistance to hydraulic scour. Well-indurated sandstone beds offer the most resistance and tend to hold up as ledges. However, the resistant ledges collapse when undercut by intense hydraulic scouring of the weakly resistant, underlying shales.

95. The rock underlying the channel at Lewisville consists entirely of dense, dark-gray clay-shale of the Eagle Ford Formation (also Cretaceous but immediately above the Woodbine stratigraphically). The clay-shale exhibits outstanding uniformity and lacks significant large-scale discontinuities.

96. Figures 39 and 40 show the preflood spillway channels at Grapevine and Lewisville, respectively, on USGS topographic maps. The differences in gradient, width, and shape between the two channels are noteworthy. The Lewisville channel is practically straight for 1/2 mile and is 600 ft wide throughout this length. The gradient of the Lewisville channel is about 0.5 percent, although it steepens to about 1.7 percent for a short stretch near the railroad.

97. The Grapevine channel course followed a small, previously incised, steep and somewhat tortuous stream for the first 1/2 mile. The channel gradient is about 2.0 percent upstream of the road (point A on Figure 39) but steepens to 8 percent just downstream of the road (built on the downstream end of the sandstone ledge forming the foundation of the spillway structure).

98. The only place where noteworthy erosion occurred at Lewisville was downstream in the vicinity of the railroad bridge (Figure 40). The severe erosion which threatened the Grapevine structure was initiated just downstream from the road (Point A, Figure 39). In both cases these were the locations of the steepest gradients. In the case of Grapevine, the sharp gradient change also corresponded to a lithologic discontinuity which formed an encroaching waterfall too close to the structure.

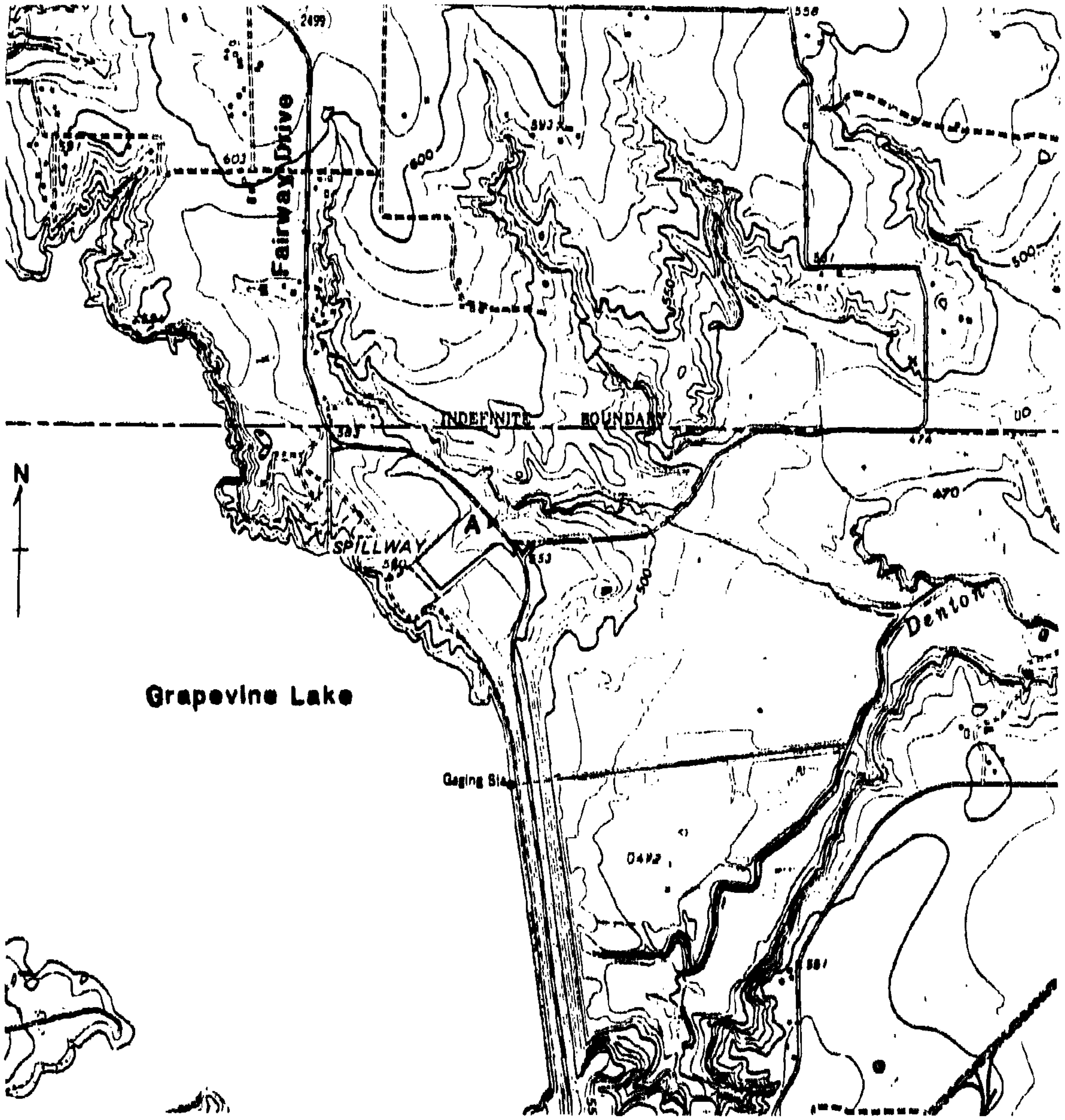


Figure 39. Spillway at Grapevine Lake, from Grapevine 7-1/2 min topographic quadrangle (1959), 10-ft contours. Spillway crest left center (Note the marked increase in gradient where the road crosses spillway channel (Point A)--severe erosion originated at this knickpoint)

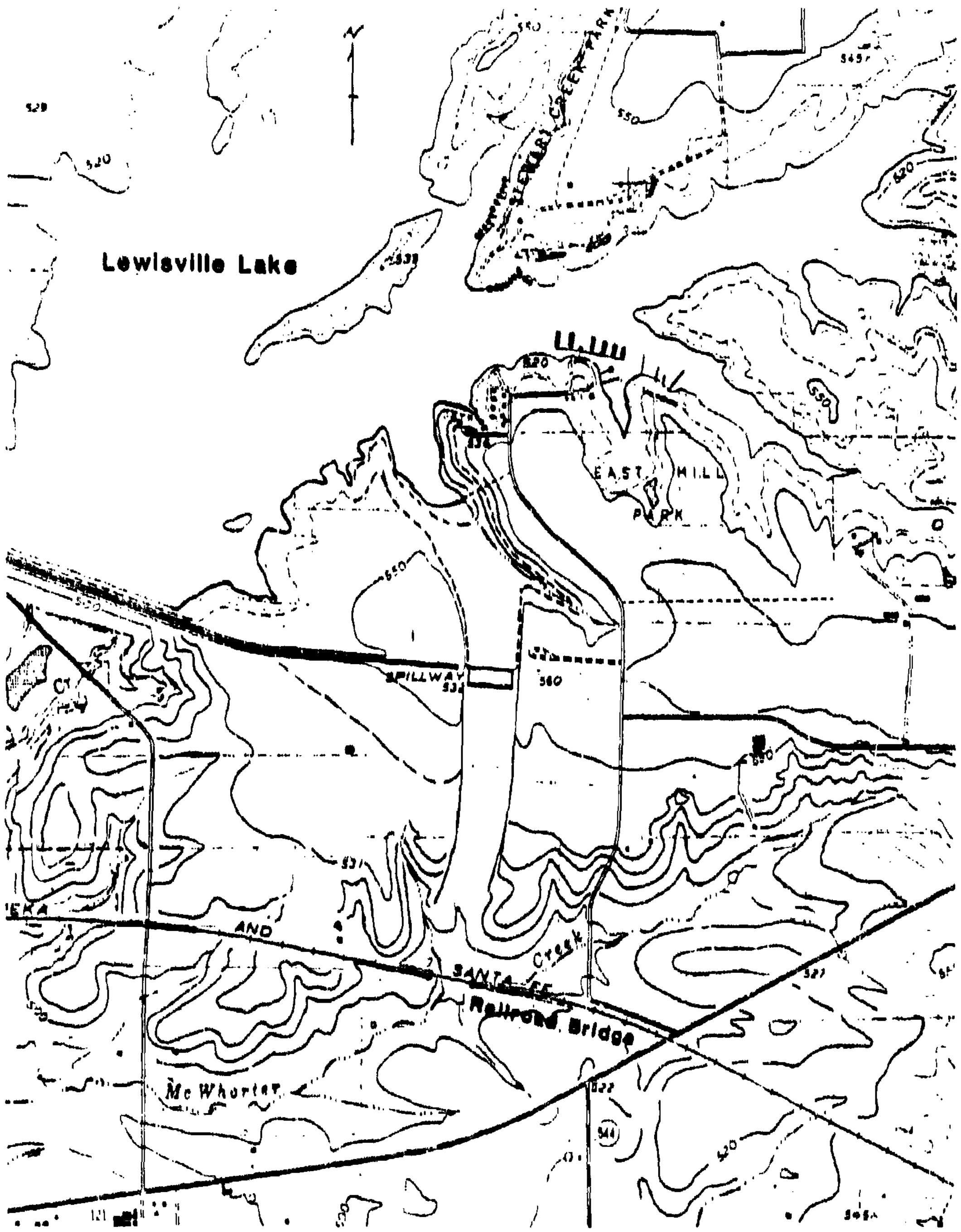


Figure 40. Spillway at Lewisville Lake, from Lewisville East 7-1/2 min topographic quadrangle (1960), 10-ft contours. Spillway crest is in the center of the figure (Note slight increase in gradient near railroad, lower center)

99. A severe headward erosion in response to spillway channel gradient change and associated lithologic discontinuity is common to several CE facilities including Grapevine (SWF), Saylorville (NCR), and non-CE Lake Brownwood (Texas). The vertical lithologic discontinuities result in differential scour which occurs along a series of erosional steps or benches. A headward knickpoint erosion is a particularly serious form of erosion in a spillway channel because it has the capacity to undermine the channel to a point where damage to costly facilities may occur. Non-CE case histories being documented include the DMAD Reservoir which was catastrophically released when headward erosion of a knickpoint undermined the spillway and caused it to fail. Documentation of the widespread occurrence of this type of spillway erosion led to a recommendation for specific research treating knickpoint erosion, particularly the effects of lateral and vertical geologic discontinuities on the rate and mechanisms of headward advance (see Part V).

Geological Factors

100. Major geological factors thought to control channel response to spillway flow, particularly erosion of the materials flooring and bounding unlined channels, include (a) discontinuity of rocks and soils and (b) erodibility of rocks and soils.

Discontinuity of rocks and soils

101. This initial study indicates that scour patterns and intensity are strongly influenced by discontinuities within the rock and soil forming unlined channels. Although the concept of "discontinuity" in rocks generally embraces any interruption in lithologic and physical properties (e.g., mineralogy, rock fabric, structure, etc.), severe channel erosion response to emergency spillway flow appears to be governed more by changes occurring on a megascopic scale rather than on a microscopic or grain-to-grain basis.

102. Depositional discontinuities are typically bedding planes, bed-to-bed contacts including erosional surfaces, and large-scale rapid changes in sedimentary structure and texture. Textural changes might involve, for example, a shift from coarse, conglomeratic sandstone to finely laminated, silty sandstone within the same bed. The structural discontinuities include faults, fractured and brecciated zones, and joints. Finally, a type of discontinuity often overlooked involves dissolution cracks and cavities. Dissolution

features are most common in carbonate and evaporite terranes, but since dissolution is the result of chemical weathering and erosion, they can also be found in other rock associations as well. A complete discussion of rock discontinuities is contained in Murphy (1985).

103. The erosion of soft, poorly resistant sediments is mitigated by large-scale lithologic continuity in gently dipping strata. Bed thickness can be an important factor with thicker units generally having more potential to maintain continuity over longer distances compared with thin units. However, because bed thickness is also controlled by Paleo-depositional environments, the above generalization has many exceptions. Again, each situation must be appraised within the context of its regional and local geologic setting.

104. At both Lewisville (SWF) and Sardis (LMK) spillways, weakly resistant shales form smooth unbroken surfaces largely free of sudden gradient change. In both cases, the discharge channel erosion in successive flow events was relatively slight. Erosion of the Sardis spillway channel during flow events of up to 81 days duration was further mitigated by a substantial energy dissipation structure at the toe of the spillway weir.

105. Conversely, it can be stated with some degree of assurance that the erodibility of spillway channels (cut or otherwise situated in soft sediments) is decidedly increased by rapid facies changes between units of variable induration, fracturing, and jointing. In all those cases, where geological factors played an apparently significant role in spillway erosion, it was found that lateral and/or vertical bed-to-bed discontinuity is a dominant parameter in terms of the effect of scour intensity and magnitude on the spillway rock.

106. The idea that discontinuities in earth materials influence erosion during high-level spillway flow is consistent and compatible with the concept that a major hydraulic control involves abrupt changes in channel gradient. Such changes are most often directly influenced by large-scale depositional and structural discontinuities such as stratigraphic pinchouts (e.g., sandstones wedging out abruptly against shales), dissolution features (such as those common to carbonate and evaporite rocks), intrusive igneous contacts, and those resulting from tight folding and faulting of rock.

107. Construction of a cut spillway channel which does not follow a preexisting stream course is often necessary in dam construction. These spillways with their wide, even floors provide for optimum passage of spillway

discharge when vegetation is restricted to low grasses or turf. However, cut spillways may be more susceptible to "first flow" erosion than a spillway which follows a natural (albeit widened and perhaps straightened) stream course, all other factors being equal.

108. In the natural system, the spillway follows a preexisting stream course which was stabilized or at least had approached geomorphic stability. In such systems, there is a tendency for the stream to "follow" rock discontinuities. Differential erosion may diminish as the natural system finds equilibrium over time.

109. The cut spillway in sedimentary rocks may transect the strata at some angle to the dip direction, and this may enhance the effect of some discontinuities in terms of their response to scour. For example, if flow is perpendicular to a sharp lithologic change (e.g., an indurated sandstone in contact with a fractured deeply weathered shale), a hydraulic jump may develop in response to the sudden rise or drop caused by differential erosion between the two units. A knickpoint may develop as a function of scour, undercutting the more resistant of the two units. This happened at the Saylorville spillway but since the water flowed over a hard, resistant sandstone, headward erosion was held up at the knickpoint for the duration of the flow. Note that the hydraulic force of high-level flow in most CE spillway channels is sufficiently great that the erosion of deeply weathered shale or similarly loosely bonded materials is easily explained; they are simply "washed out."

110. The same general phenomena will occur if the strike of interbedded strata or other geologic discontinuities is oblique to the flow. An oblique strike may cause the flow to be diverted at contacts where the less resistant unit is differentially eroded. Such diversion may affect both the channel floor and banks with successive "switchback" diversions occurring each time similar discontinuities are encountered downstream. This is comparable to the deviation experienced by a drill string each time the bit encounters rock of different abrasion resistance or hardness at an oblique angle.

111. The sudden nature of emergency spillway flow and empirical observations suggests that the geological controls of an erosion response model act in proportion to the magnitude of a given flood event. As previously discussed, the hydraulic force of the large-scale event tends to overwhelm small-scale controls with most energy being expended against large-scale discontinuities. The CE dams and reservoirs are generally large and usually built using

conservative design criteria with respect to flood frequency and magnitude. An emergency spillway flow can be a major event involving high peak flows of relatively short duration, hence the emphasis on large-scale discontinuities or those described, in terms of bedding, by Deere (1964) as "thin" (2-1/2 in.), "medium" (12 to 13 in.), "thick" (36 to 120 in.), and "very thick" (>120 in.).

Erodibility of rocks and soils

112. Erodibility is defined in the current AGI Glossary of Geology as "the quality, degree, or capability of being eroded or yielding more or less readily to erosion." This study is concerned mostly with the rate at which rock and their derived soils will erode during spillway flow and the volume of sediment that will be removed and transported downstream.

113. Erodibility and its rate are not well understood and are therefore difficult to define exactly. Both depend, to a great extent, on widely varying physical properties such as density, abrasion resistance/hardness, compressive strength, and engineering parameters such as cohesiveness and condition of discontinuity. Condition of discontinuity describes rock mass quality from the standpoint of roughness, degree of weathering, jointing characteristics, solution openings, and cavity-and-space fillings (Murphy 1985).

114. To treat the problems of erodibility and erosion rates of soil and rock flooring a spillway channel, a parameter or aspect which unifies or integrates engineering parameters to a single property or term is needed. The scale of the hydraulic forces generated during high level flows suggests that rippability may serve as a good point of departure in describing the relative resistance to erosion of the soil and rock flooring unlined spillway channels.

115. Rippability was proposed by Weaver (1975) as a rock mass classification system that enables the assessment of the excavation characteristics of earth materials and provides a guide for the assessment of bulldozer or backhoe ripping capability. The major geological features which govern the assessment of rippability are rock type, hardness, weathering, structure, and fabric. Seismic P-wave velocity has also been found to be an index of rippability. Rippability may be attractive from the standpoint of assessing rock erodibility because it combines rock aspects which tend to highlight discontinuity of material strength (and hence the potential for differential erosion to occur) in a spillway channel. Rippability should be combined with a factor

that describes lithostratigraphic continuity in order to derive the erosion potential of the rock from a geotechnical standpoint.

116. Although rippability may adequately describe the erodibility of surface exposures, it must be kept in mind that spillway erosion often excavates channels to significant depths during overflows. A combination of rippability with other parameters derived from exploration drilling (e.g., rock-quality designation) may be required to extrapolate erodibility to appropriate depths. At the same time, slope stability may play a role in the wholesale erosion of discharge channels eroded to significant depths during overflow events.

PART III: IMPACTS OF EMERGENCY SPILLWAY FLOWS

117. Dams are artificial elements superimposed on natural drainages. Given time, a drainage system will adjust to the new condition both upstream and downstream from the damsite. The outlet works pass variable volumes of water which maintain minimum stream flows and which, over time, approximately equal the amount of water input to the system. The natural system in most cases is allowed to slowly find a new stability or approximate equilibrium. This concept is central to the design philosophy of flood control projects which regulate the flow, and hence the quasi-stability, of the downstream system. Flood events that result in high discharge through outlet works can induce instability in the downstream network.

118. The unregulated emergency spillway flow is a random external factor which acts to promote channel instability downstream. These flows are of high intensity, often of relatively short duration, and frequently subject spillway channel beds to high hydrodynamic stress. A natural analog that approximates this type of catastrophic event is the effect of strong storm-water runoff (flash flooding) in stream systems. In both cases, the system will respond to the suddenly imposed condition in one or more ways.

119. The response to catastrophic emergency spillway flow events includes channel floor and bank erosion, sediment transport and deposition, and overbank flooding. Case histories which highlight these impacts were presented in Part I of this report. Such effects are not restricted to the immediate area of the dam where they occasionally threaten spillway structures. These flows can act to cause stream thresholds* (which limit change on the system) to be exceeded in the main channels into which the spillway flows and hence can influence or induce changes for significant distances downstream.

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* A threshold is a boundary or entrance to a new domain, (AGI 1972). Schumm (1973) popularized the use of this term in stream geomorphology in his classic paper, "Geomorphic Thresholds and Complex Response of Drainage Systems." Commonly used as a concept in fluvial channel flow studies, thresholds are crossed whenever the channel (fluvial) process is changed. For example, a stream will not erode its channel until a certain threshold, controlled by the energy acting on the channel, is reached. At that point the stream process changes from one characterized by nonerosion to one involving active erosion and (most often) transportation of locally derived sediment. Another threshold is crossed when the stream loses its capacity to transport sediment, and deposition of eroded materials commences.

For example, a knickpoint migration and headcutting are often initiated at a point considerably downstream from a control structure.

120. It is important to note that not all spillway flows cause stream thresholds to be surpassed, and therefore not all flows will seriously influence main channels downstream. The prediction of when and where spillway flows will impact downstream thresholds cannot be accomplished at this time and will constitute a research recommendation (see Part V).

Channel Floor and Bank Erosion

121. Erosion of the rocks flooring an unlined spillway channel is probably the most serious of all flow impacts. Experience shows that channel floor degradation can undermine spillway structures (Figure 41) and can threaten reservoir integrity (e.g., Grapevine and DMAD). The initiation, rate, and extent of erosional downcutting are controlled by gradient change, flow volume and velocity, and nature and variability of channel floor lithology and structure.

Figure 41. A 30-ft waterfall now occupies the site of the failed downstream spillway apron at a private reservoir on Johnny's Creek near Fort Payne, Alabama. Excessive scour undercut the concrete structure during an estimated 100-year storm in the summer of 1985

122. Channel bank erosion during high-level spillway flow widens the spillway channel, thus involving the loss of rock, soils, and vegetation to the flow. Case histories illustrate that trees can build up as log jams and cause damage or loss to downstream structures such as bridges (e.g., Enid Reservoir, LMK). Alternatively, trees left toppled in a spillway channel can jam and impede subsequent spillway flows (Figures 42 and 43). This circumstantial influence can cause local scour, sediment transportation, and deposition and can act to endanger some upstream structures.

123. In many cases, emergency spillway flow results in both channel widening and degradation. Excellent examples include both Saylorville (NCR) and Grapevine (SWF). There is a tendency to pay more attention to channel degradation than to channel bank erosion because the former would appear to play a bigger role in the threatening of a spillway structure than the latter. Further investigation may reveal that equal attention should be paid to the interrelation of channel degradation and widening, at least in some specific instances. To cite one instance--at Saylorville, the degradation and widening have caused the right spillway channel bank to oversteepen and slump (Figure 44). This failure will result over time in a considerable amount of unconsolidated rock and soil sliding into the channel. The accumulation of this sediment in the channel may influence the spillway's capacity to pass future flows. At the very least, it will add considerably to the sediment volume that will be transported and deposited in the downstream reaches of the main channel during a future spillway overflow.

Sediment Transport and Deposition

124. Sedimentation in spillway channels, main-channel confluences, and downstream reaches can become a problem whenever significant erosion has occurred upstream. In such cases, the sediment load is derived from the rock and soil forming the channel floors and banks because the water flowing over the spillway crest is almost clear.

125. Sediment deposition in a spillway channel can impede passage of the reservoir overflow and, by deflecting flow into the channel banks, cause irregular channel widening. Such deposition can occur when an obstacle of sufficient size causes local energy loss and reduces the capacity of the flow to transport its load. Anything that impedes spillway channel flow may act to

Figure 42. Remains of small suspension bridge destroyed by 1984 flow at Broken Bow Dam (Oklahoma). The flow widened the spillway channel and undermined trees, which piled up on the bridge

Figure 43. Trees undermined by channel widening at Grenada Dam emergency spillway (Mississippi)

Figure 44. Slope failure in right bank of Saylorville (NCR) spillway outlet channel. The slope was undermined by erosion of the channel floor during 1984 overflow

endanger upstream structures and constitutes a reasonable cause for concern.

126. Sediment deposited on fan deltas and bars at main-channel confluences (Figures 45 and 46) and in downstream reaches can conceivably initiate or accelerate erosion of streambanks and levees. The sudden influx of sediment to main channels may impact navigation, endanger ecological balances, and increase the danger of flooding downstream. The 1973 spillway flow at Sardis Dam (LMK) resulted in the deposition of a considerable volume of sediment in the main channel--so much so that it was impossible to pass normal flows through the outlet works without causing overbank flooding downstream. The removal of this material by dredging was required to alleviate the problem.

Flooding

127. Emergency spillways are not designed to prevent flooding. Their purpose is to prevent the overtopping of the dam and its possible failure during rare flood events for which it is impractical to store all floodwaters. However, it is true that an emergency spillway flow can create a significant downstream flooding problem and may also contribute to that already occurring.

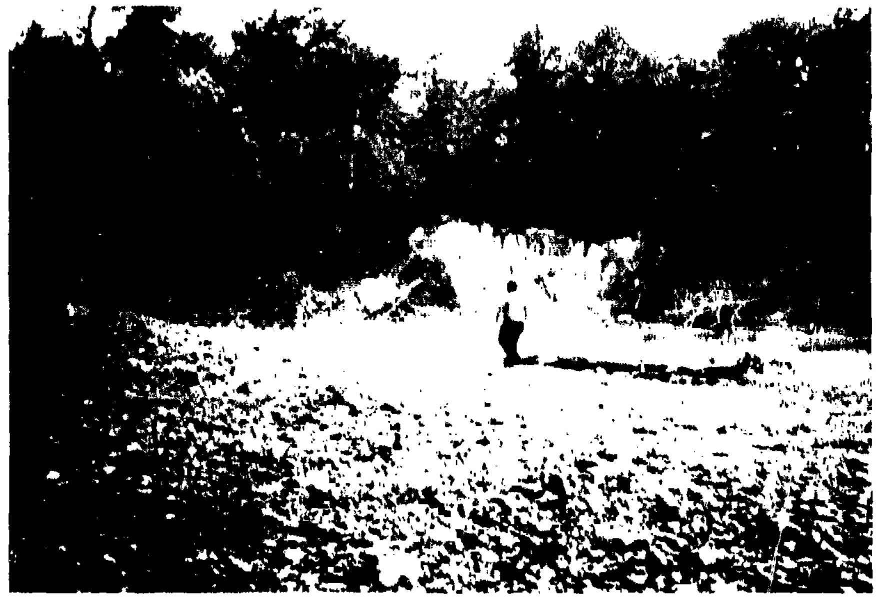

Figure 45. Gravel fan formed by spillway overflow at Wister Dam (SWT) Tulsa District. Formation forced flow against outer channel bank causing bank erosion

Figure 46. Fan formed in French Creek, Union City project, by deposition of eroded emergency spillway rocks. Creek sedimentation has impacted downstream fish populations

128. Overbank flooding as a function of spillway flow is analogous to that experienced by any stream-channel system--it occurs when water volume exceeds the capacity of the watercourse. Flooding will occur in either case when the channel is not sufficiently deep and wide to accommodate a sudden large flow volume. Cut spillway channels are usually designed to pass large flow volumes. Natural channels, on the other hand, will not pass the large volume of water associated with floods unless they have previously experienced an event of sufficient magnitude to significantly widen and deepen the channel. Such channels are often not underfit to the natural system but are clearly inadequate to the large spillway flow event. This is an acute problem because emergency spillway flow at dams in many basins occurs when anomalous precipitation is widespread and the natural system is already swollen with tributary floodwaters.

129. Serious damage and loss of property can occur when erosion causes failure of the spillway and catastrophic release of the reservoir. When the DMAD Reservoir drained because of erosion-induced spillway failure, the Gunnison Bend Reservoir downstream had to be breached (Figure 47) to avoid overtopping of its earthen dam from the sudden large influx of floodwaters. Breaching the reservoir triggered severe flooding of the communities downstream when already swollen channels received sudden additional flow.

Figure 47. Intentional breaching of spillway at Gunnison Bend Reservoir, Utah, during 1983 flood

PART IV: EVALUATION OF EMERGENCY SPILLWAY CHANNELS

130. Because spillway erosion is a phenomenon with hydrologic, hydraulic, engineering design, and surface and subsurface geological controls of channel response, spillways should be evaluated by multidisciplinary teams of professionals with backgrounds in the above fields. The CE District offices that may be experiencing serious spillway channel erosion for the first time are urged to consult with those who have prior experience with this problem in other CE Districts, at WES, or in other Federal agencies.

131. As well as making a detailed site inspection, the evaluation team should collect the flood history of the dam facility along with other pertinent data (e.g., design specifications, modifications, regional and site geology, and geotechnical information, hydrographic records, old maps, aerial photos, etc.).

132. Because numerous factors can combine in several ways to create erosion problems, it is useful to outline a checklist of basic questions which should be answered for a comprehensive spillway evaluation. Since this study is in its initial phase, the list is probably not complete. Any comments and/or suggestions on improving the checklist should be submitted. The preliminary checklist is as follows:

a. Have changes in the hydrologic data base resulted in changes in the spillway design discharge?

b. If so, is the spillway structure and channel design adequate to pass the PMF discharge?

c. Have changes occurred in downstream infrastructure (particularly urbanization and/or industrial development) that necessitate reevaluation of the impacts of spillway overflows?

d. Is there any evidence of recent downstream or upstream changes in stream channel morphology?

e. Has the spillway flowed or nearly flowed previously?

f. What percent of design discharge did previous flow(s) represent?

g. What was the duration of previous flow event(s)?

h. What happened at the spillway structure, in the channel, at the confluence with the main stream, and downstream in the main channel reaches during previous spillway overflows?

i. Does videotape, film, or other photographic documentation of previous flow events exist?

j. What is the channel gradient? Is it uniform?

k. What geological factors control gradient change in the channel?

l. How will the gradient change(s) alter channel hydraulics?

m. Is the spillway channel a cut (excavated) feature or does it follow a natural, preexisting drainage?

n. Are there sharp bends, constrictions, or other obstacles to flow in the channel?

o. Can the channel pass design flows without overtopping of its banks or significant enlargement of bank-to-bank dimensions?

p. If the spillway has not experienced overflow, is the data base adequate to assess the erosional impacts of the first flow?

q. Are spillway borings sufficient in number and appropriately spaced to assess lithologic composition and continuity as well as rock-mass properties?

r. Is the seismic P-wave velocity of the rocks underlying the channel known?

s. Can a detailed geologic map of the channel bottom and banks be constructed with the available data (e.g., at scales of 1:600 and 1:300)?

t. Is the channel sited in a homogeneous lithology which maintains continuity downstream for at least 2,000 ft?

u. Do discontinuities coincide with channel knickpoints; are they incipient knickpoints?

v. How much material was removed from the spillway during prior flow events?

w. Where was the eroded material deposited during prior flow events? Was the sediment deposition detrimental?

x. If the spillway has not experienced flow, can good estimates be made of the volume of material likely to be removed for various flow scenarios? How will sediment deposition impact the channel, its confluence with the main stream and downstream reaches?

y. Will spillway channel flow more likely result in channel degradation or bank erosion?

z. Will spillway channel erosion impact bank stability?

aa. What will be the consequence of bank instability should it occur?

bb. Would spillway flows result in serious restriction of access to the dam and prevent proper operation of the facilities or hamper emergency operations?

cc. Would spillway flows result in serious restriction of access to the dam and prevent proper operation of the facilities or hamper emergency operations?

dd. Is there anything about the spillway that could lead one to suspect that a significant overflow could impact the safety of the main embankment and its ancillary structures and/or adjacent recreation facilities (natural or cultural obstacles or obstructions in the spillway channel that could impede flow, for example)?

133. The level of remedial measures recommended by the evaluation report will normally fall somewhat on a "best case" to "worst case" continuum. The former involves spillways that will probably never experience flow or those floored in homogeneous "hardrock," such as granite. For example, at the Isabella Dam (Kern River, California) the excellent concrete spillway structure will probably erode faster than the granite forming the spillway channel bottom (Figure 48). The Isabella Dam furnishes a bounding case on the nonerosive side.

134. A worst-case evaluation might document a very large reservoir upstream from a high-value infrastructure, an underdesigned spillway structure

Figure 48. Upstream view of the excavated emergency spillway discharge channel at Isabella Dam, California. The channel floor and the left bank were excavated in very hard granite. The right wall is of concrete

with no energy dissipation structures, a downstream channel underlain by non-cohesive soil which shows frequent litho-stratigraphic changes, and finally, precursor erosion indicators such as sudden gradient changes and large pits in the channel bottom. As previously described (Part I), the Sam Rayburn spillway fits most of the above worst-case conditions.

PART V: CONCLUSIONS AND RECOMMENDATIONS

135. The documentation of the impacts and controlling factors of erosion during an emergency spillway overflow has identified specific research needs to solve the problems for which the present state of knowledge is insufficient. This is particularly true for problems such as an accurate prediction of erosion rates, the impact of spillway flow on downstream channel reaches, and cost-effective remedial and preventive measures.

Conclusions

136. Channel response to spillway flow is controlled by the following major factors:

- a. Flood frequency, magnitude, and duration.
- b. Engineering design of the spillway structure and spillway discharge channel.
- c. Channel gradient and changes in channel gradient.
- d. Discontinuity in rocks and derived soils.
- e. Erodibility of rocks and derived soils.

All of the above factors are to varying degrees interrelated and often act in concert. In particular, stratigraphic or structural discontinuity in rock spillway channels often controls changes in channel gradient, and hence the initiation and rate of headward (knickpoint) erosion.

137. Spillway channel responses to emergency flow can include the following major impacts:

- a. Undercutting by erosion and loss of the spillway structure.
- b. Catastrophic loss of reservoir waters.
- c. Channel floor and bank erosion (which can lead to bank instability).
- d. Sediment transport and deposition.
- e. Overbank flooding.

Any or all of these responses can occur during a given overflow event. However, the erosion of rocks flooring an unlined spillway channel is regarded as the most serious of all flow impacts since channel degradation can cause structural failure of the spillway and catastrophic release of the reservoir.

138. Detailed spillway evaluations require expertise in geological interpretation and hydraulics engineering experience and should therefore be conducted by multidisciplinary teams of professionals with backgrounds in these fields.

Recommendations

Research in progress

139. The results of this study indicate that research in the following three specific areas will improve the capabilities for predicting the rate and intensity of scour in unlined spillway channels as well as the impacts of such erosion in downstream portions of the system:

a. The influence of stratigraphic discontinuities on the initiation and rate of spillway channel flow erosion in sedimentary rocks (including the effect of channel gradient on erosion and the effects of geologic discontinuities on channel gradient).

b. The correlation of spillway channel performance with possible "erodibility indices" such as rippability (seismic velocity, rock type, hardness, weathering, structure, fabric), and litho-stratigraphic continuity.

c. The response of emergency spillway channels to catastrophic flows including downstream impacts of rock erosion in emergency spillway channels.

The recommended research will also improve capabilities with respect to the selection of effective preventive and remedial measures in channels where the risk of excessive scour appears high. Details of the proposed research are discussed in Appendix C.

Data base amplification

140. As several important projects were not visited in FY85, the data base inventory is incomplete and should be expanded via further site inspections in FY86. The following sites should be investigated in detail:

a. The Cochiti and Jemez Reservoir spillways in New Mexico (SWA) should be evaluated in FY86. The Southwestern Division performed an evaluation of dams and listed these spillways as having high erosion potential.

b. Field studies should be performed at the DMAD Reservoir, Utah, to determine preflood geologic and hydraulic conditions in the spillway channel. Spillway failure and release of the 16,000-acre-ft reservoir followed rapid headward erosion of a knickpoint in the spillway channel during the floods of 1983. This evaluation should attempt to document the control(s) that stabilized the knickpoint for 48 hr during the overflow.

_c_. The Pat Mayse spillway (SWT) should be evaluated in detail. A generous design freeboard suggests that this spillway may never operate, but this aspect needs further investigation as do the potential impacts of spillway overflow on the easily erodible shales and siltstones which form the floor of the channel.

_d_. The Bear Creek Omaha District (MRO) and Cherry Creek (MRO) Reservoir spillways are upstream from high-cost infrastructure and should be examined during FY86.

_e_. A private reservoir in the Johnny's Creek area near Fort Payne, Alabama (SAM), suffered severe erosion-induced spillway failure during an August 1985 flood. Onsite investigation of this failure is recommended.

141. The investigation of more of the smaller private structures that exist throughout the United States might prove valuable. Most of these structures have uncontrolled open-cut spillway channels in a wide variety of materials. These spillways operate frequently as they are often placed at or only a few feet above the normal conservation pool. Information from these spillways could add significantly to the data base regarding erodibility of various rock types under a multitude of conditions.

142. More attention must be given to remedial and preventive measures implemented to solve or impede erosion in unlined spillway channels. Further inquiry and documentation in this vital area are strongly recommended.

143. The data base for this work unit should be managed by its desktop computer system which includes a hard disk and a Modem. The desktop system could be tied to the WES central processing and mass storage units. This would facilitate editing, technical report and engineering manual(s) production, and permanent data-file storage and would provide easy access to these data by other WES laboratories. An authorized information transfer by desktop telecommunications could be accomplished by expanding the local area network to include interested District personnel, other Federal laboratories, and interested coworkers in other agencies. Flood event and spillway overflow advisories together with other information pertinent to this and other REMR efforts should be posted to a computer-driven "REMR Bulletin Board." This mechanism would provide a rapid means of multiple-party information transfer without recourse to conventional telephone and written communiques.

144. To effect timely technology transfer, it is recommended that WES organize a workshop to include invited delegates from each Corps District plus interested parties from the USDA Soil Conservation Service and the Bureau of

Land Reclamation. The delegates with particular expertise or experience in the problem of bedrock erosion associated with spillway overflows should be asked to compile a paper to be presented orally at the workshop. The workshop should be held over a 3-day period in Des Moines and include a field trip to the Saylorville spillway. The edited proceedings of the workshop should be produced as a publication as it would comprise a valuable addition to the data base. The workshop should be conducted in FY87.

145. It is also recommended that the three videotapes documenting spillway flows at Black Butte, Saylorville, and the DMAD Reservoirs be edited, combined with other visual documentation and lecture materials, scripted, professionally narrated, and produced as a supplement to the final technical report and/or engineering manual.

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APPENDIX A: DATA BASE ACQUISITION

1. Site visits, case histories, and materials derived from literature searches comprise the data base compiled during the initial phase of the work unit "Rock Erosion in Emergency Spillway Channels." A substantial portion of the data base is derived from District experience with spillway flows. Twenty-five projects were visited in FY85, as described in Appendix B.

2. Generally, District reports, contacts with Division and District personnel, and data derived from Periodic Inspection Reports during Repair, Evaluation, Maintenance, and Rehabilitation (REMR) visits to Division and District offices guided the selection of site visits. The visits to District offices were made to obtain records of spillway performance and to make direct contact with the District personnel most knowledgeable of a particular dam's operation and history. Subsequent visits to project sites with project and/or District personnel contributed substantially to the observational data base. The data base is supported by photo documentation and trip reports, the summaries of which are presented in Appendix B.

3. The REMR work unit acquired videotapes of three spillway overflows that provide valuable visual documentation of erosion in unlined channels. One of these tapes dramatically documents a spillway failure and catastrophic release of a large, privately owned reservoir during the West Millard County (Utah) floods of 1983 (the DMAD Dam disaster). This film highlights the "domino" effect produced by erosion-induced collapse of an unused downstream structure, extraordinary headward migration of the resulting knickpoint in the spillway channel, futile last-ditch efforts to save the spillway structure, and its final failure. Downstream impacts produced by sudden release of the 16,000-acre-ft reservoir are also well illustrated. These impacts include forced breaching of the 7,000-acre-ft Gunnison Bend Reservoir and consequent flooding of the town of Deseret and surrounding farmlands.

4. Other important film documentation in the data base includes the US Army Corps of Engineers (CE) produced videotape of the 1984 Saylorville, Rock Island District (NCR), spillway flow and a Bureau of Land Reclamation videotape of the 1983 spillway flow event at Black Butte Reservoir, US Army Engineer District, Sacramento (SPK).

5. Data-base acquisition and management are an ongoing mission of this work unit. Several additional CE and non-CE sites have been selected for visits during FY86. During the same period, the entire data base should be compiled on Waterways Experiment Station computers to facilitate rapid access and dissemination of trip reports, research results, and entries to the REMR Notebook.

APPENDIX B: SUMMARY OF SITE VISITS

1. Summaries of site visits are organized according to US Army Corps of Engineers (CE) Divisions and alphabetized by project name. After each summary, a listing of the major factors (geologic and hydraulic) which influence spillway channel erosion at the site is given. Positive factors are those which impede erosion or minimize its impact. Negative factors are those which enhance the rate of erosion and heighten impacts on the channel and its downstream reaches.

South Pacific Division

Black Butte Dam

2. Black Butte Dam is an earth-fill dam that was completed in 1963. It is located on Stony Creek, which rises in the Coast Range and flows eastward into the Sacramento River. The damsite is located in low rolling foothills. Geologically, most of the materials in the dam and reservoir area are fairly soft sedimentary rocks of Tertiary Age; however, there is a flow-basalt unit with some associated volcanic breccia in the section, and this unit is present at the immediate damsite, including the spillway alignment.

3. The Black Butte emergency spillway channel flowed for the first time in March 1983 for 66 hr. The maximum height of water over the spillway crest was 2.7 ft and maximum spillway discharge was 1,640 cfs. This event was not a major flood; it was in the range of a 10- to 70-yr return interval. The channel experienced moderate erosion downstream of the crest (Figure B1), but the erosion did not endanger the structure.

4. The spillway channel is cut through horizontally bedded basalts interlaminated with pyroclastic material. A flat, reinforced-concrete slab was constructed at the channel floor crest. The channel gradient upstream of the crest is 0 percent, but downstream of the crest it is 9 percent. The grassed soil fill and the pyroclastic material were differentially eroded downstream of the spillway crest. More downcutting occurred when the spillway channel lithology changed from the basalt to the underlying Tertiary sediments in the lower portion of the channel. Because of the highly heterogeneous structure of the channel rock, with cooling cracks varying in intensity from place to

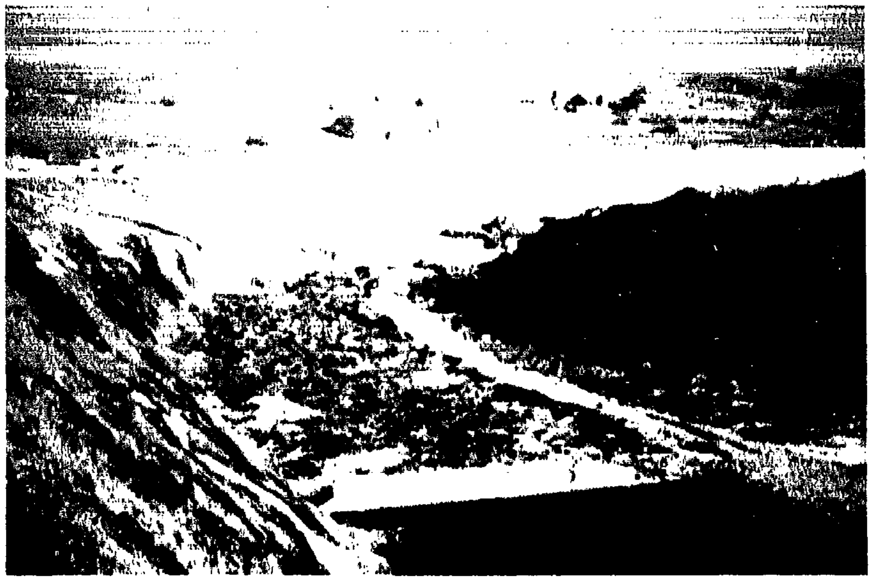

Figure B1. Downstream view of eroded Black Butte spillway following 1983 overflow. The spillway floor is composed of basaltic and pyroclastic materials. The reinforced-concrete spillway weir is in foreground. The linear structure, right center, is a road used to haul materials for remedial dam work several years before overflow

place, differential scour was very irregular and a series of natural cascades formed at the terminus of the basalt flow unit.

5. It is striking to compare the condition of the spillway floor upstream and downstream of the sill. The same volumetric flow was obviously present in both sections. In the upstream section with its 0-percent gradient, the water velocity was relatively low and the floor undisturbed and covered with cobble-sized gravel. In the downstream section with its 9-percent gradient, water velocity and kinetic energy were high and scour was widespread, especially in the lower portions of the channel. This scour is acceptable and currently does not threaten the spillway structure during floods of this magnitude and frequency. However, for major floods the steep downstream channel gradient and the narrow width of the channel conveyance suggest that erosion will be severe in areas of structural and stratigraphic discontinuity as cited above.

6. The spillway channel discharges into an old borrow pit, which is about 100 acres in size and forms a shallow lake. The spillway erosion resulted in the formation of a debris delta fan at the edge of this pit. There

is plenty of reserve capacity in the pit for trapping sediment resulting from any future spillway discharges.

Positive factors:

- Engineering design: favors minimal scour at the spillway structure.
- Downstream impacts are minimal.

Negative factors:

- Lithologic inhomogeneity of channel floor materials.
- Stratigraphic discontinuity of channel floor materials (at a point distant from the spillway structure.
- For major floods, the channel width appears somewhat limited. The steepness of the gradient ensures further scour downstream of the structure.

DMAD Dam

7. The data base includes a videotape which dramatically documents spillway failure and catastrophic release of a large, privately owned reservoir during the West Millard County (Utah) floods of 1983 (the DMAD Dam disaster). This film highlights the domino effect produced by erosion-induced collapse of an unused downstream structure, extraordinary headward migration of the resulting knickpoint in the spillway channel, futile last-ditch efforts to save the spillway structure, and its final failure. Downstream impacts produced by the sudden release of the 16,000-acre-ft reservoir are also well illustrated. These impacts include forced breaching of the 7,000-acre-ft Gunnison Bend Reservoir and consequent flooding of the town of Deseret, irrigation systems, and surrounding farmlands.

8. The erosion-induced failure of the old diversionary structure 2 miles downstream of the dam created a knickpoint approximately 15 to 20 ft in height in the spillway channel. In 1 week's time, this knickpoint migrated to within a few hundred yards of the DMAD spillway where it stabilized for 2 days. It is suspected that a change in channel lithology impeded the knickpoint migration, but this should be confirmed by examination of the preflood geological data. Once the knickpoint began to erode upstream again, it did so at the rate of 1 ft/min. At this point, the project personnel and a sheriff's posse began to place concrete-filled cars in the downstream channel adjacent to the weir. This action was unsuccessful. The waterfall undercut the spillway structure foundation and sidewall embankments, and the spillway failure and release of the 16,000-acre-ft reservoir followed immediately thereafter.

9. Follow-up work to determine preflood geologic and hydraulic conditions in the spillway channel are planned for the next report period.

Negative factors:

- Engineering design: failure to remove the unused structure downstream resulted in its collapse during flooding and the formation of a steep knickpoint in the spillway channel.
- Soft, noncohesive soils (mapped as Holocene and Pleistocene valley fill) underlying spillway channel.

Salinas Dam

10. Salinas Dam is a thin wall concrete arch structure built in the early 1940s as a war-emergency measure to provide a water supply for Camp San Luis Obispo. The emergency spillway comprises an ungated overflow sill immediately adjacent to the dam proper at the right abutment and a curved concrete apron downstream of the sill. The curved concrete apron, about 110 ft long on its centerline, is superelevated (like an auto racetrack) so that at high flows the water is evenly distributed across the apron's width. At low overflows, only the left low part of the apron is wetted.

11. At its lower edge, the spillway apron terminates abruptly at a lip. During overflows, water free-falls from this lip and lands on a rock surface several feet below. The rock surface is a dip slope, dipping southeastward, roughly parallel to the lower portion of the apron. The geologic formation is a massive Cretaceous sandstone with very few shaly interbeds.

12. The spillway overflows frequently--on the average from one to three times a year. The maximum recorded overflow had a depth of 12.31 ft above the spillway crest and a volume of 14,600 cfs. By the late 1960s, and especially after the high flows of 1969, cumulative erosion damage had occurred, particularly along the right rock bank. A remedial program of rock bolting, wire-mesh installation, Guniting, and placing of mass concrete in the rock floor was carried out in late 1969. Since this repair, the Gunite has held up against erosion, the wire mesh is torn in places, and some of the mass concrete in the floor has been eroded (Figure B2). The spillway and spillway channel appear to be in excellent condition.

13. The massive, relatively homogeneous, sandstone forming the spillway channel will erode at a slow rate, but minor repairs such as those described above are probably sufficient to maintain the integrity of the structure.

Positive factors:

- Stratigraphic continuity of channel floor rock.
- Lithologic homogeneity and durability of channel floor rock.

Negative factors:

- No obvious problems.

Figure B2. View (1985) of the right bank of the spillway channel at Salinas Dam showing antierosion remedial measures installed in 1969--Guniting, wire mesh, and mass concrete poured in spillway floor

North Pacific Division

Blue River Dam

14. The Blue River Dam is located 1.8 miles above the confluence of the Blue River with the McKenzie River approximately 42 miles east of Eugene, Oregon. The dam is a gravel-filled embankment with an impervious earth core, a regulating tunnel, intake tower, a gated concrete spillway, and a stilling basin. The design discharge of the spillway is 31,100 cfs with velocities of 8 ft/sec. The spillway was used for a 25-day period at a discharge of 2,600 to 2,800 cfs during the construction of a plug in the temporary outlet tunnel. During this period, severe erosion occurred at the discharge terminus of the channel.

15. The channel is excavated in hard-to-moderately-hard andesite of the Little Butte Volcanic Series (Oligocene to Miocene). Joints, shear zones, fractures, and zones of hydrothermal alterations highlight discontinuities in this highly variable and complex rock. A District erosion investigation report completed in September 1984 concluded that the primary controls of the channel scour are jointing, broken rock in shear zones, and hydrothermally altered zones. The report recommended the removal of small trees from the spillway and the placing of concrete or asphalt lining in the channel to prevent further erosion.

Positive factors:

- Recorded and anticipated scour does not appear to threaten structure.

Negative factors:

- Lithologic heterogeneity and structural discontinuities.
- High design velocities.

Missouri River Division

Bear Creek Dam

16. The 8,100-ft-long Bear Creek emergency spillway is cut into a very durable shale. The gradient of the channel floor is 0 percent until it drops off into a natural drainage system on the downstream end. The spillway has never experienced a flow event; however, small amounts of water overflowing from a nearby irrigation canal have caused some minor erosion of the channel rock. These small flows have removed a weathered surface veneer of shale and formed a small gully on the downstream end of the channel. Riprap has been placed to prevent erosion during future low flows. A major spillway flow would probably remove a great deal of surficial weathered material, but the good condition of the durable rock below the zone of surface weathering would probably prevent excessive scour. Gullying and headcutting, should they occur, will be located at the downstream terminus of the channel.

Positive factors:

- Durability and continuity of unweathered shale below the zone of surface weathering.
- Potential for severe scour located at a point distant from the spillway structure.

Negative factors:

- Surficial weathering of the shale.

Chatfield Dam

17. The Chatfield Dam emergency spillway con ts of a large, ungrated, concrete-lined chute with a conventional hydraulic jump stilling basin. Water cresting the spillway structure will flow into a shallow cut channel and then into the South Platte River. The spillway has never flowed. No erosion problems were seen at this project or reported by site personnel. No future problems are expected with this type of spillway structure other than downstream channel widening.

Positive factors:

- Engineering design.

Negative factors:

- No obvious problems.

Cherry Creek Dam

18. The Cherry Creek emergency spillway consists of an excavated canal from the Cherry Creek Basin to the West Toll Gate Creek. The spillway has a design horizontal length of approximately 11,000 ft. The spillway channel does not flow into the Cherry Creek drainage basin but into a tributary basin of the South Platte River. This design is intended to divert floodwaters around the city of Denver during overflows. However, it should be noted that the area around the project and in adjacent drainage basins has been developed and is now essentially urbanized. This spillway has not experienced an overflow.

19. Side slopes of the spillway approach channel have experienced minor erosion, resulting in some sloughing. The elevation of sloughed material deposits is el 5,608.7* which is 10.7 ft greater than the design crest, el 5,598. Therefore, the reservoir would have to be 20 ft higher than the design elevation before it would begin to flow over the spillway weir.

20. No erosional problems have been reported downstream of the spillway, although erosion has been experienced at the outlet of the spillway with another creek. However, the channel is narrow and steep. The high-cost downstream infrastructure provides good justification for a more detailed evaluation of this spillway.

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* For this appendix, elevations are in feet NGVD.

Positive factors:

- Conservative design, no record of overflows.

Negative factors:

- High-cost infrastructure downstream.
- Steep channel gradients along narrow cut.

Southwestern Division

Benbrook Dam

21. The notched ogee spillway weir at Benbrook Dam (Figure B3) has experienced two overflow events. No serious erosion resulted from the spillway releases. The channel is cut into durable limestone units of the Fredricksburg Group (Lower Cretaceous) interbedded with thin shale beds. At the downstream end of the spillway discharge channel, the lithology changes to an alluvial sand. Directly upstream of this lithologic change, the channel narrows because the rock is very competent and had to be blasted to facilitate excavation.

Figure B3. Notched ogee spillway weir at Benbrook Dam, Texas

22. The overflows did very little damage to the channel where it is underlain by resistant limestone. Gullying and degradation took place in the alluvial sand but was distant from the concrete structure. Some shallow

gullying has occurred downstream of a knickpoint created by a highway which crosses the spillway channel floor. This erosion is only removing loose, weathered material but would serve to concentrate future spillway flows, albeit these excessive erosion problems are not envisaged.

Positive factors:

- Durability of the bedrock underlying channel in proximity to the spillway structure.

Negative factors:

- Channel constriction in the lower reaches will increase water velocity just above contact with noncohesive soils.
- Knickpoint formed by the road crossing the spillway channel.

Broken Bow Dam

23. The Broken Bow emergency spillway is a gated overflow weir cut across a synclinal structure in Paleozoic chert, sandstone, limestone, tuff, and shale. A spillway overflow of 7 days duration in 1984 widened the spillway channel and washed out a downstream box culvert bridge, but erosion did not threaten the spillway structure.

24. Some erosion problems exist at a regulation dam located 5 miles downstream of the main embankment. The regulation dam is an overflow weir with five low-flow windows and a sloping flip bucket. Thinly bedded quartzitic sandstones, siltstones, and shales of the Mississippian Age Stanley Group dip moderately in a downstream direction in the adjacent channel. These sediments are being eroded as overflows peel sediment blocks that break along bedding planes and fractures. In one place, on the downstream side, the erosion has undercut the concrete structure. The rate of erosion is slow, having progressed over many flow events. The problem is being monitored closely by site and District personnel.

25. This project is a good example where a lack of adequate downstream right-of-way has impacted the CE operation of the dam. State-owned small log dams prevent the expedient removal of spillway waters. During spillway releases, the water backs up near the downstream dam toe and prevents inspection for piping erosion. The CE personnel are legally constrained from removing the state structures during floods.

Positive factors:

- Engineering design: gated spillway.
- Erosion problems remote from spillway structure.

Negative factors:

- Downstream dip of thinly bedded sediments, structural and stratigraphic discontinuities in sediments forming channel floor downstream from regulation dam.
- Differential weathering of lithologies forming channel floor.

Georgetown Dam

26. The Georgetown Dam emergency spillway is cut into thickly bedded limestone units of the Lower Cretaceous Age. A concrete sill approximately 1 ft thick is keyed into the crest of the channel floor. This spillway has not experienced a flow.

27. The limestone foundation is very durable and resistant to erosion. Weathering of a surface veneer will cause minor erosion to occur during a spillway flow. The continuous nature of the strata suggests that significant downcutting or headward erosion will be minimal in overflow events.

Positive factors:

- Durability of limestones forming the spillway channel.
- Continuity of limestones forming spillway channel.

Negative factors:

- Weathering of bedrock will result in the removal of a thin veneer of rock during overflow events. Severe erosional impact(s) is not anticipated.

Granger Dam

28. The Granger Dam emergency spillway is an overflow weir with a 1V-to-3H slope and energy dissipators in the plunge pool. The spillway channel is cut into erodible shales of the Lower Cretaceous Age and has a smooth gradient with no knickpoints. Weathering of the shales has produced a surface of loose clay. This weir design removes much of the water's kinetic energy and its ability to erode. No erosion problems are anticipated during a future spillway flow.

Positive factors:

- Engineering design.
- Lithologic and stratigraphic continuity of shale forming spillway floor.

Negative factors:

- Spillway flow will remove a loose surface veneer of weathered shale. The resulting erosional impact is expected to be minimal.

Grapevine Dam

29. The Grapevine Dam emergency spillway recently underwent rehabilitation following the damages incurred during a 1981 overflow event. The original spillway structure was an overflow weir with a V-shaped downstream apron. During the 1981 flow, the spillway channel was enlarged and experienced severe gullying and headward erosion. The discharge through the spillway peaked at 9,100 cfs flowing at approximately 35 to 40 ft/sec, and was about 5 percent of the Spillway Design Flow (SDF) (191,000 cfs). It was considered that a larger flow could have caused excessive scour to undercut the spillway weir and thus cause the release of the reservoir. The rehabilitation program, completed in October 1985, involved the construction of a large stilling basin, the relocation of Fairway Drive across the existing spillway apron, the addition of a berm on the downstream face of the embankment, and the construction of additional roads and recreational facilities in one of the parks, all at a cost of $11 million. Details of the factors which caused failure of the Grapevine spillway channel are reported in Parts I and III of this report.

Positive factors:

- The existing concrete spillway was not damaged by the passage of the 1981 flood.

Negative Factors:

- Engineering design: lacks energy dissipation structures at the toe of the spillway apron.
- Substantial gradient change in the spillway channel.
- The spillway channel was incised by an "underfit" array downstream from the sharp gradient change mentioned above.
- Relatively soft, weakly cohesive sediments of the Cretaceous Woodbine Formation are characterized by poor lithologic and stratigraphic continuity.
- A paved road crossed the spillway channel in close proximity to the structure. The road dammed spillway overflow and contributed to the initiation of knickpoint erosion in the channel.

Lewisville

30. The Lewisville Dam ogee spillway also experienced overflow in the fall of 1981. Because Lewisville and Grapevine are only 10 miles apart, it was assumed that meteorological conditions were approximately the same in both areas. Flow peaks and duration were also similar. However, spillway channel erosion at Lewisville was much less severe than that at Grapevine and was never structure threatening. Factors contributing to this difference include

the excellent durability and lithologic continuity of the Eagle Ford Formation (Cretaceous) shale unit underlying the Lewisville channel and the existence of a gentle, smooth gradient for a considerable distance downstream.

Positive factors:

- Excellent continuity of the durable shale underlying the spillway channel.
- Smooth, gentle channel gradient.
- Wide, flat, channel bed.

Negative factors:

- Weathered shale "skin" easily removed by erosion; not a serious problem.
- An abrupt change in channel direction and gradient in the downstream reaches of the channel.

Pat Mayse Dam

31. The emergency spillway at Pat Mayse Dam is an uncontrolled and unlined channel excavated in poorly cohesive shales and siltstones of the Cretaceous Eagle Ford Formation. A small, but actively eroding, gully on the downstream end of the channel attests to the highly erodible nature of the channel material. In a manner analogous to the preflood situation at Grapevine, a highway embankment crossing the channel causes an anomaly in the channel gradient. The embankment has been lined with riprap to reduce the stress that would be applied to the channel during a flow event. The spillway crest is 26 ft above the conservation pool elevation and has never flowed.

32. The spillway channel will experience severe downcutting and headward erosion should the spillway ever operate at significant proportions of design discharge. Because no concrete spillway structure exists, a release of the reservoir could occur if the spillway experienced flow for a significant duration or experienced large flow volumes.

33. It is recommended that this spillway be evaluated in detail. The generous design freeboard suggests that the spillway may never operate, but this conclusion needs further investigation and verification as do the potential impacts of a possible spillway overflow.

Positive factors:

- Conservative design freeboard.

Negative factors:

- Lack of a concrete spillway structure.
- Spillway channel is underlain by poorly cohesive sediments and soils.

Sam Rayburn Dam

34. A comprehensive reconnaissance investigation of the Rayburn emergency spillway weir and downstream floodway confirmed the potentially serious spillway channel erosion problem (US Army Engineer District, Fort Worth 1984)* and Part I of this report. These reports also contain recommendations for remedial and preventive action.

35. The Sam Rayburn project is on the Angelina stream system. It consists of a large earthen dam, a gated hydroelectric dam, and an emergency drop spillway weir which is small and primitive in comparison to the first two structures. The B. A. Steinhagen Dam (Dam "B") is located approximately 12 miles downstream and serves as a resettling reservoir for the hydroelectric dam outflow.

36. The Rayburn spillway has never operated. However, in 1974 sustained rains saturated east Texas. Successive storms caused the water level in the reservoir to jump alarmingly, and the pool rose to within 3 ft of the spillway crest. Resident engineers claim that one or two additional storms would have resulted in an overflow of the spillway weir.

37. The Rayburn spillway channel is a 2,200-ft-wide cut-and-fill feature excavated in soft-to-moderately-hard shaly clay, fine-to-medium-grained loose sand, and hard, well-cemented, fine-grained indurated sandstone, all belonging to the Catahoula Formation of the Oligocene Age. The excavated material was used as fill to level the spillway floor area. The fill areas are classified as highly erodible.

38. There seems to be universal agreement that a significant overtopping of the spillway weir could cause a severe spillway channel erosion and the possible loss of the structure. This failure would occur under the conditions outlined above at a time when the surrounding region is saturated and severe flooding is occurring downstream on a swollen Neches system. The loss of the Rayburn spillway could result in the loss of the Dam "B" structure as

* References in this appendix are cited at the end of the main text.

well. The waters of both reservoirs would then flow into the Neches Valley with catastrophic downstream consequences.

Positive factors:

- Apparent very low frequency of spillway overflow event. The spillway has not experienced an overflow event to date.

Negative factors:

- Engineering design: revised hydrologic estimates increased the depth of Project Maximum Flood (PMF) spillway flow by 68 percent, from 7.1 ft to 11.9 ft above the spillway crest.
- Increased importance of the reservoir in terms of flood control, hydroelectric power, recreation use, and cost of downstream infrastructure.
- Wide, excavated channel narrows on the right side and enters a draw with restricted conveyance.
- Channel is underlain by soft, easily erodible, noncohesive sediments and fill with poor lithologic and stratigraphic continuity.
- Channel undergoes two gradient increases in its first 2,000 ft downstream.
- Recreational vehicular traffic (mud derbys) in the spillway channel is causing deep pitting of the floor (precursor erosion element).

Tenkiller Ferry Dam

39. The emergency spillway structure at the Tenkiller Ferry Dam is a gated weir with a downstream apron and flip-bucket. Massive jointed sandstone underlain by shale and thinner sandstone units of the Pennsylvanian Atoka Formation forms the foundation of the spillway structure. A spillway overflow in 1957 produced considerable erosion of this rock. The event prompted the Tulsa District to extend the small apron and add the flip-bucket. Only minor flows have occurred since the 1957 event and none of these have damaged the structure.

40. A major overflow could remove large pieces of the sandstone foundation and damage parts of the concrete structure. However, because of the extended apron, the loss of this structure would probably not occur.

Positive factors:

- Engineering design: extension of the apron and installation of an energy dissipator have enhanced the structural integrity of the spillway.
- Low frequency of major flow events.

Negative factors:

- Stratigraphical and structural discontinuities in spillway channel rock.
- Channel gradient is very steep.

<u>Waco Dam</u>

41. The gated overflow weir emergency spillway at the Waco Dam has never experienced a flow. The spillway channel lithology consists of a Cretaceous shale unit which is prone to surficial weathering. This weathered surface would be easily removed during a spillway overflow. Below the depth affected by surficial weathering, the shale is durable and (given its continuity) not particularly susceptible to excessive scour near the spillway structure.

42. Further downstream the spillway channel transects a fault which juxtaposes the shale and a less cohesive clay unit. This discontinuity could trigger downstream channel bank erosion in the clays.

Positive factors:

- Durability and continuity of the bedrock shale near the spillway structure.

Negative factors:

- Weathered shale is very susceptible to removal by scour during initial flow.
- Downstream channel bank erosion in weakly consolidated clays is a possibility during initial overflow event.

<u>Wister Dam</u>

43. The Wister uncontrolled concrete weir and spillway channel is underlain by interlaminated sandstones and shales of the Pennsylvanian Age. A homogeneous shale section dominates channel lithology further downstream. The sedimentary rocks dip downstream at approximately 30 deg (Figures B4 and B5).

44. The Wister spillway has operated three times since the dam began operation in 1949. In both 1957 and 1984, the spillway flowed for approximately 10 days with peak flows near 2,200 cfs. Loose fill with vegetation was removed and rock eroded along both concrete layback walls and in the middle of the channel. Downcutting during both overflows took place downstream of a channel gradient anomaly created by a resistant sandstone unit. Erosion took place by differentially lifting and stripping thin sedimentary strata along weak bedding planes and fractures. The structure was not endangered in either flow event.

Figure B4. Transverse view of emergency spillway at Wister project showing dipping-resistant sandstone beds of the Pennsylvanian Age

Figure B5. Downstream view of Wister spillway channel. Channel floor materials are sandstones (foreground) and shales (middle and far background)

Positive factors:

- Durability of strata in spillway channel.

Negative factors:

- Dip of sedimentary units lends structural and stratigraphic inhomogeneity to the section.

North Central Division, Saylorville Dam

45. The Saylorville spillway channel experienced flow for the first time during the period 18 June to 3 July 1984. Although the spillway structure was not endangered by this event, the erosion of the spillway channel was severe. A dramatic "stair step" erosional landscape with up to 30 ft of local relief was produced in the gently dipping, indurated shales, calcareous siltstones, thin limestones, coals, and sandstones that floor the spillway channel. These sediments are part of the Cherokee Group of the Des Moines Series which is Lower Pennsylvanian in age. District hydrologists estimate that the events which produced spillway flow were sustained, high flows amounting to a 100-yr volume flood with flows peaking at a 10-year flow frequency. Peak flow (17,000 cfs) and velocities on the upper spillway channel occurred on 22 June, 4-1/2 days after the overflow commenced. According to the US Army Engineer District, Rock Island (1984), the total outflows from Saylorville were regulated by adjusting the releases from the outlet conduit and the erosion occurred essentially as predicted. For flows greater than 20,000 cfs, the estimated erosion remains a prediction with little observational experience.

46. Excellent studies of the spillway geology were conducted in 1981-82 in response to North Central Division recommendations in 1979. The Division expressed concerns as to the ability of the spillway to pass design floods without overtopping the walls of the spillway chute. The 1984 spillway flow demonstrated that the spillway performs per engineering design. In any case, the excellent geologic studies conducted before the first flow event combine with excellent visual documentation and detailed studies of the flood and erosion in the spillway channel to yield an outstanding observational data base for a well-documented case history of rock erosion in a spillway channel.

47. A study of air photos and topographic maps made before the flood of 1984 shows that precursor controls of erosion in the spillway channel were clearly in place before the spillway overflowed. A small pilot channel with a

single meander was present immediately downstream from the spillway weir. The terminus of the meander was controlled by an abrupt change in lithology--a competent sandstone bed forming the floor of the upstream channel wedged out suddenly to soft underlying shales interbedded with thin carbonates. Downstream from this contact the channel gradient steepened abruptly and the precursor erosion channel formed a narrow, straight course. It was at this contact, a knickpoint, that severe erosion occurred during the 1984 overflow. However, the resistant sandstone held up headward erosion of the knickpoint at contact and safeguarded the spillway structure. Serious downstream impacts include a slope stability problem in the large right channel bank (formed of soils and glacial till) where it was steepened by severe downcutting of the channel.

Positive factors:

- Durability and continuity of the rock adjacent to the spillway structure.

Negative factors:

- Poorly cohesive sedimentary rock underlying downstream portion of the spillway channel.
- Lack of lithological and stratigraphical continuity in the sedimentary rocks underlying the downstream portion of the spillway channel.
- Narrowing of the downstream portion of the channel focuses flow and accelerates channel bank and bottom degradation.

Lower Mississippi Valley Division

Caddo Lake

48. Caddo Lake is a constant elevation reservoir that receives flow from Lake O' the Pines. It has two spillways or drop structures--the upstream structure is an overflow concrete wall, whereas the downstream structure is an overflow weir. Both structures are constructed on Wilcox Group sediments (Eocene). The tailwater is maintained downstream from both structures and inspection of any scour that may have occurred was not possible. No channel bank erosion was occurring downstream of either structure.

Positive factors:

- Engineering design.

Negative factors:

- None known.

Enid Dam

49. The concrete chute overflow weir at the Enid Dam has operated adequately during two flows (1978, 1983) since it was brought into operation in 1952. The emergency spillway channel was widened and deepened and a small bridge was destroyed during a 67-day flow in 1973. This flow event had a maximum volume of 4,170 cfs. A 15-ft-deep scourhole was formed approximately 150 yd downstream of the concrete apron, but the durability of a lignitic clay bed (mapped as part of the Eocene Claiborne Group) kept the knickpoint from migrating upstream.

50. It is recommended that the thickness and lateral extent of this unit be researched so that its future performance can be estimated.

Positive factors:

- Engineering design: large stilling basin and baffle blocks at toe of the downstream apron.
- Apparent stratigraphic continuity and durability of lithology forming the channel floor in the downstream channel.

Negative factors:

- No obvious problem.

Grenada Dam

51. The uncontrolled chute and overflow weir (Figure B6) have operated successfully three times since construction was completed in 1954. The first two flows produced only minor channel widening, but a 180-day overflow in 1983 widened the channel extensively and created a scour hole downstream of the stilling basin. Channel widening caused many trees to topple into the spillway channel. These trees could form a logjam during a future overflow, trigger overbank flooding, and cause erosion of high-cost park facilities. It is recommended that fa len trees be removed from the spillway channel. Structure threatening erosion is not anticipated at this site.

Positive factors:

- Engineering design: large stilling basin and baffle blocks at the downstream toe of the spillway apron.
- Continuity and durability of Claiborne Group shale (Eocene) in the downstream channel.

Figure B6. Uncontrolled overflow weir and chute at Grenada Dam, Mississippi

Negative factors:

- Channel widening has toppled many large trees in the spillway channel. These trees should be removed before a future spillway overflow.

Sardis Dam

52. The ungated spillway weir with a large vertical drop and energy dissipators at the Sardis Dam has experienced two overflows. The first flow enlarged a pilot channel from "a ditch you could step over" to a 50-ft-wide by 30-ft-deep channel. The eroded material was deposited in the outlet channel and lake where it promoted flooding and hindered normal operation of the outlet works. This material was removed by dredging. The spillway channel was shaped and the second overflow did little damage other than some minor bank erosion downstream where the channel turns. Structure-threatening erosion problems are not anticipated at this site.

Positive factors:

- Engineering design: Large stilling basin containing baffle blocks at the downstream toe of the spillway apron.
- Continuity and durability of the Tallahatta Formation shale (Eocene Claiborne Group) in the downstream channel.
- Good conveyance.

Negative factors:

- The weathered shale will erode and the channel may continue to widen, particularly at the downstream bend. The transported material may again have to be dredged from the downstream main channel reaches to avoid overbank flooding.

Ohio River Division

Laurel River Dam

53. The Laurel River Dam has an emergency spillway with an "inverted-U" design. This design utilizes upstream and downstream aprons keyed in walls. The sill is capped by a reinforced concrete slab (Figure B7). Spillway overflows occur, on the average, twice a year. The spillway channel is situated in a massive sandstone which is underlain by an alternating sequence of thin-bedded sandstones, shales, and massive sandstone (Figure B8). A knickpoint has formed where the upper massive sandstone is being undercut by erosion of the poorly cohesive shale unit. The rate of knickpoint retreat is approximately 3 ft/yr. Although erosion is occurring, its rate is constant and excessive scour will not threaten the spillway structure in the near future.

Positive factors:

- Durable sedimentary rocks underlying the weir.
- Engineering design.

Negative factors:

- Lack of stratigraphic continuity.
- Spillway channel knickpoint not stabilized.
- Easily erodible shale controlling headward migration of the knickpoint. This unit controls the rate of erosion at this site.

Union City Dam

54. The Union City Dam spillway is an ungated notched weir with a downstream apron. The spillway channel is cut into a thinly bedded shale. The channel floor has experienced considerable degradation immediately downstream of the apron. District personnel are planning to add a concrete drop structure at the toe of the structure to prevent undercutting of the apron thus slowing the rate of channel degradation.

55. The shales tend to rip along bedding planes and fractures. The walls, which were cut on a vertical slope, are still in excellent condition. Further downstream, mechanical weathering of rock occurs because of seasonal

Figure B7. Reinforced-concrete overflow weir at Laurel River Dam, eastern Kentucky

Figure B8. Thin-bedded sandstones and shales, spillway discharge channel, Laurel River Dam

freezing and thawing. Resulting erosion in this part of the channel is slow and does not threaten the structure.

Positive factors:

- Planned remedial works will remove threat of excessive scour at the spillway structure.

Negative factors:

- Shale exhibits weakness along bedding planes and fractures. These discontinuities tend to be amplified by freeze/thaw mechanical weathering.

APPENDIX C: RESEARCH PROPOSALS

1. The results of this study indicate that research is needed in three specific areas to enhance the capabilities to predict the rate and intensity of scour in unlined spillway channels as well as the impacts of such erosion in downstream portions of the system (this research is currently under way at the US Army Engineer Waterways Experiment Station (WES)). The research areas are:

- a. The influence of stratigraphic discontinuities on the initiation and rate of spillway channel erosion in sedimentary rocks (including the effect of channel gradient on erosion and the effects of geologic discontinuities on channel gradient).
- b. The correlation of spillway channel performance with possible "erodability indices" such as "rippability" (seismic velocity, rock type, hardness, weathering, structure, fabric) and lithostratigraphic continuity.
- c. The response of emergency spillway channels to catastrophic flows including downstream impacts of rock erosion in emergency spillway channels.

The recommended research in these three areas will also improve capabilities with respect to the selection of effective preventive and remedial measures in channels where the risk of excessive scour appears high. For example, techniques such as lime stabilization may be applicable in some unlined spillway channels. Low-cost preventive measures sorely need further inquiry.

Influence of Stratigraphic Discontinuities

2. The major factors controlling erosion and other responses to spillway flow identified by this study include the interrelated effects of hydraulic gradient change and the geologic discontinuities in earth materials. Because hydraulic anomalies are so often the direct result of structural or stratigraphic discontinuities, it is logical to assume that these two factors can act in concert to enhance scour potential in an unlined channel. Work to date indicates that these factors combine to initiate and control headward migration of knickpoints where resistant rock layers are undercut by scouring of softer underlying strata. Knickpoint erosion and headward migration are the most dangerous form of erosion from the standpoint of potential for catastrophic failure of spillway structures as is shown by the DMAD Reservoir

spillway failure in Utah and spillway channel erosion at the Grapevine and Saylorville Reservoirs.

3. Little is known about the quantitative effects of stratigraphic or structural discontinuities on erosion rates in sedimentary rocks. In this context, a recent US Department of Agriculture Soil Conservation Service report summarizing the national effort in erosion research states that the effect of stratigraphic variability on erosion needs to be addressed by applied research.

4. The purpose of the proposed research is to determine the influence of lateral and vertical stratigraphic variability on the initiation and rate of erosion in sedimentary rocks. Laboratory tests will be conducted by using the WES Geotechnical Laboratory self-contained recirculating and tilting hydraulic flume. The data provided during the first phase of the research could be utilized in a larger flume modeling effort in cooperation with the WES Hydraulics Laboratory.

5. The Catahoula Formation (Oligocene-Miocene) of the Gulf Basin has been selected as a model to represent a sequence characterized by stratigraphic discontinuity in poorly cohesive and noncohesive sands, silts, and clays. Because repeatability is an important aspect of the research approach, materials that simulate the physical properties of the Catahoula sediments will be designed and fabricated. Flume tests will determine the individual rates of erosion of these materials. Experiments will then be conducted by using interstratified materials of varying thicknesses, strengths, homogeneity, and lateral continuity so the influence of stratigraphic discontinuity on the erosion rates of individual units can be analyzed. Attempts will then be made to analyze the effects of fractures and other structural discontinuities on erosion rate(s) in the same materials.

6. The experimental results will be carefully documented and compared with the measured impacts of spillway overflows of specific sites such as Grapevine, Saylorville, and DMAD Reservoirs. The experimentally derived results should provide useful input to hydraulic and mathematical modeling efforts. The results should also prove useful in the design of exploration programs aimed at predicting the rate of unlined spillway channel erosion on a site-specific basis.

Erosion Indices

7. The US Army Corps of Engineers (CE) manages too many projects for each to be visited and evaluated by a WES work unit. The same holds true for colleagues treating the erosion problems of projects controlled by other Federal, state, and local agencies. Methods leading to the forced-ranking or priority of projects are desirable with the result that problem sites are identified and treated promptly.

8. The varied factors controlling the rate and intensity of bedrock erosion during high-level spillway overflows (see Part II of the main text) must be weighed and combined to produce a quantitative estimate of erodibility for each site within a given District or area. The use of a functional "erosion index" or an "erosion probability index" should allow comparison of estimated erosion rates and impacts of spillway overflow on a project-by-project basis within and between Districts.

9. It is recommended that research be devoted to the problem of correctly weighting the individual factors which control erosion and other responses to spillway overflow. At present it appears likely that the rock-mass parameters that govern rippability, combined with litho-stratigraphic continuity factors, may provide predictive erosion indices from a geotechnical point of view.

10. Rippability has been proposed by several authors as a rock-mass classification, or rating, that enhances engineering judgment with respect to the assessment of the excavation characteristics of earth materials and bulldozer or backhoe ripping capability (Weaver 1975,* Engineer Technical Letter (ETL) 1110-2-82, and Engineer Manual (EM) 1110-2-1802). The rock-mass parameters from which a rippability rating (RR) is derived include rock type, hardness, weathering, structure (strike and dip orientation, joint spacing and continuity, fracture, cleavage, sedimentary structures), and fabric. Seismic P-wave velocity has also been found to be an index of rippability when used judiciously on a comparative basis with RR.

11. Rippability may be attractive from the standpoint of assessing rock erodibility (especially with respect to the scale of hydraulic forces acting on unlined channels during CE spillway overflow) because it combines rock

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* References in this appendix are cited at the end of the main text.

aspects tending to highlight discontinuity(ies) of earth material(s) strength--hence the potential for differential erosion to occur in an emergency spillway discharge channel. Rippability should be combined with a factor describing vertical and horizontal litho-stratigraphic continuity in order to derive the erosion potential of the rock from a geotechnical standpoint. Hydraulic factors controlling rock erosion during an emergency spillway overflow are being developed by the WES Hydraulics Laboratory. A period of time must also be given for developing a method that will combine these factors correctly and allow for ranking spillway channels according to their susceptibility to scour during overflow events. At present, it is thought that methods utilizing additive and multiplicative probability formula concepts offer the best opportunity for success in this difficult area, but more work is clearly needed.

12. The erosion indices produced by factor analysis or integration will be tested by comparison with well-documented case histories that contain a maximum amount of preflood information in the records. The Saylorville Reservoir and Lake Brownwood spillway channels have suffered extensive erosion damage and, in this regard, offer excellent examples as do several other projects where spillway overflows produced minimal impacts on channels and downstream reaches. Erosion indices produced by factor analysis and/or integration will also be tested during the above-mentioned flume-testing experiments.

13. Results of this research will be promulgated via a technical report and may be included in an engineering manual produced by the work unit participants. These results should be immediately useful to District personnel responsible for spillway channel evaluation and maintenance, Division and District planning and budgeting personnel, and interested parties working on the same problem in other Federal, state, and local agencies.

Response of Emergency Spillway Channels to Catastrophic Flow

14. Major responses to sudden spillway releases can include channel floor and bank erosion, sediment transport and deposition, and overbank flooding. These responses are discussed in some detail in Part II of the main text. The primary objective of this research is to determine the threshold point where erosion is initiated and to predict some quasi-equilibrium state where the eroded channel will stabilize.

15. Channel degradation produced by sudden spillway release is the most serious of sudden flow impacts. In some cases it is obvious that downstream impacts can ultimately have disastrous effects at the upstream control structure. For example, knickpoint migration and headcutting are often initiated at a point considerably downstream from a control structure. As discussed previously, channel floor erosion is a function of interrelated hydraulic and geologic factors. Determining the relative effects of these factors on erosion thresholds and channel equilibrium will form a major part of the channel response research.

16. Although most emphasis is logically directed toward those erosion processes which can endanger spillway structures, the serious downstream effects of spillway overflow and erosion are also documented. The extensive erosion of bedrock in some unlined channels often results in a considerable influx of eroded material into the main channel during a very short time span. Rock fans and sandbars can be deposited in the main channel at its confluence with the spillway exit channel. Such events can impact navigation channels, trigger stream and levee bank erosion, and cause serious environmental concerns with respect to fish and wildlife habitats. Channel degradation and widening can cause spillway channel banks to oversteepen and slump, an impact that could affect the channel's capacity to pass future overflows.

17. The impacts cited above are largely known through experience and observation. Most of the responses to spillway channel overflow have some sort of analog to those occurring in response to uniform flow in natural open channels. However, research in the field of sediment transport has been largely confined to uniform and steady flow conditions with regard to water discharge as well as sediment load. This approach is generally acceptable because anomalies in sediment transport characteristics, because of turbulence and nonsteady flow, propagate very slowly along most natural stream systems. However, high-level emergency spillway releases involve very dynamic turbulent flows which impart sudden, very high hydraulic stresses to the channel and its downstream reaches.

18. To fully understand the impact of spillway releases on the channel and its downstream reaches, thresholds and responses must be estimated for the entire stream system. Research should determine the characteristics that control a stream's response to external impacts, such as sudden spillway release, for one or two well-known drainage basins. The study should determine the

characteristics unique to the system and the upstream and downstream extent to which the dam impacts the stream system. Finally, the study should be able to predict the nature and extent of downstream impacts resulting from high-level emergency spillway flow.